ANITA
Antarctic Impulsive Transient Antenna

A long duration balloon mission to constrain the origin of the highest energy particles in the universe

University of Hawaii at Manoa
JPL
NASA
UC Irvine
University of Delaware
Penn State
Kansas University
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[3] ... Proposal Title (Short and/or Full)

Short Title: Antarctic Impulsive Transient Antenna

Full Title: Antarctic Impulsive Transient Antenna: A Long Duration Balloon High Energy Neutrino Observatory
(1) Structure and Evolution of the Universe

ANITA will establish the first high energy neutrino observatory among NASA missions, using the entire Antarctic ice sheet as a collecting aperture for particles which originate in the most extreme environments in the universe: the inner edges of massive black hole accretion disks, the intense radiation fields within gamma-ray burst sources, and the collisions of the highest energy cosmic rays in the universe with the cosmic microwave background radiation integrated over the entire volume of our visible universe. A balloon payload at nearly 40km altitude can observe 1.5M cubic km of extremely radio-transparent ice out to its visible horizon. Neutrinos at EeV energies interact within the ice and produce an intense, compact particle shower, several m in length and cm in diameter. Pulsed radio emission from these intense showers is visible at great distances, and the radio quiet environment of Antarctica will facilitate their detection.

Cage Code: 0W411
DUNS Number: 965088057
TIN Number: 996000354

Institution Type: NASA Center

International Participation & Description: No

U.S. Government Agency Participation: Yes (Dr. Kurt Liewer, co-Investigator, JPL, $1,000,000 Dr. Charles Naudet, co-Investigator, JPL, $900,000)
[11] ... Program
Program
Selection: 

[12] ... Srotype
Proposal Type: Mission of Opportunity

[13] ... Data1
For Missions of
Long Duration Balloon (LDB)
Opportunity:

[14] ... Data2
For ISS attached
payload only:

[15] ... AddInfo
New Technology: ANITA will develop a pulse-phased low-frequency antenna array for neutrino-induced radio impulse detection. Specific new technology that will be developed is: --trigger hardware for impulse triggering in the presence of potential noise --polarization tracking algorithms for recovery of neutrino source direction --spectral discrimination algorithms for recovery of neutrino shower azimuthal angle

[16] ... AOBudget
| NASA OSS Cost (FY2003 $): | $31,899.00 |
| NASA OSS Cost (RY $):     | $34,954.00 |
| Total Cost (FY2003 $):    | $31,899.00 |
| Total Cost (RY $):        | $34,954.00 |

Continue

Edit Proposal Information
Science Objective: A Balloon-borne Ultra-high energy Neutrino Observatory

NASA Beyond Einstein themes:

• Test fundamental laws of high energy physics & astrophysics

• Probe particle acceleration processes near massive black hole event horizons

• Test the nature and origin of the highest energy cosmic rays, via the first observation of their cosmogenic neutrino partners.

Mission Overview: A long-duration balloon mission over Antarctica

• First flight in 2006-2007, two additional flights in 08-09, 09-10. Each Flight: ~15 days. Baseline Mission plan: 45 days total flight time

• Radio-frequency monitoring of Antarctic ice sheet from ~40 km altitude

• Flights are circumpolar due to continuous wind circulation around south pole

• Neutrino cascades within ice sheet produce strong Electro-Magnetic Pulse (EMP) which propagates through ice. Antarctic ice is transparent to radio waves up to ~1 GHz

• Ice sheet becomes a neutrino “converter:” neutrinos enter and radio waves come out.

• Effective telescope area: ~$10^6$ km$^2$!

Array of quad-ridged horn antennas views ice sheet out to horizon at D ~ 680 km

Utilize Askaryan effect in neutrino cascades: radio pulse mechanism tested at accelerators

~$10^6$ azimuth resolution via antenna beam gradiometry within antenna clusters

~$3^o$ elevation resolution by interferometry between top & bottom antenna clusters

Pulse polarimetry to get additional information on neutrino direction
ANITA

Balloon Gondola / Launch vehicle

- Balloon gondola plus science payload mass = 1840 kg (4050 lbs). Dual gondolas planned for 1yr turnaround.
- Power requirements = 1 kW, solar photovoltaic panels
- Gondola is anti-rotation stabilized, sun-pointing
- Long-duration balloon launch from McMurdo Station, Antarctica
- No deployments or articulations necessary during flight

Science Team: Combining Neutrino astronomy, High Energy Cosmic rays, & Ballooning expertise

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Collaborators:
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Mission Management

Principal Investigator: P. Gorham, joint position as senior staff member at JPL, and Prof. of Particle Astrophysics, University of Hawaii at Manoa

Project Management & Instrument Development: Jet Propulsion Laboratory

Gondola development: UC Irvine

Antarctic Balloon Operations: National Scientific Balloon Facility (NSBF)

Polar Programs: National Science Foundation

Schedule & Cost

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1 SCIENCE INVESTIGATION

1.1 Scientific Goals and Objectives

The primary objective of the Antarctic Impulsive Transient Antenna (ANITA) mission is to extend the reach of NASA observatories into the realm of high energy neutrino astronomy, in concordance with the vision of the theme of NASA’s Structure and Evolution of the Universe (SEU) 2003 roadmap, to test the fundamental laws of high energy physics and astrophysics. Neutrinos and gravity waves are the only direct astrophysical messengers which reach earth unattenuated through space at all energies. At the highest expected energies, neutrinos are expected to have Lorentz gamma factors in excess of $10^{22}$, based on the recent estimates of neutrino mass [1]. Such extreme particle kinematics and the conditions under which they are produced are far beyond what can be obtained at any present or future earth-based accelerator. ANITA measurements will thus probe both the nature of the sources of these extreme particles, and the fundamental interactions of high energy physics at extreme scales.

1.1.1 Primary NASA Science Themes.

1.1.1.1 SEU Beyond Einstein Primary Theme: Massive Black Holes & High Energy Physics. Neutrinos are the most penetrating form of radiation known, and are unaffected by magnetic fields or intense radiation fields, which may deflect charged particles and scatter X- and gamma-rays repeatedly. In the accretion disks that channel and accelerate matter through the event horizons of black holes, conditions are such that neutrinos are one of the few, if not the only, messenger particles that can escape unscattered and unabsorbed with information about the innermost regions. In the accretion disks surrounding Massive Black Holes (MBH), almost certain to be the engines for Active Galactic Nuclei (AGN), bulk particle acceleration is an observational fact, and neutrino emission an inevitable consequence of the decay of pions produced in the colliding matter.

Although there is general agreement that particle acceleration near the massive black holes at the centers of AGN is almost certain to produce neutrino emission that is closely tied to the MBH accretion rate [2], the level of emission is under intense debate. If accelerated protons can escape from the sources to become ultra-high energy cosmic rays, then the high energy neutrino fluxes are tied to the cosmic ray flux via an important relation first noted by Waxman & Bahcall [3], and are likely to be low—mostly inaccessible to existing neutrino telescopes. A similar, less stringent, limit comes from bounds on the extragalactic gamma-ray background from EGRET [4]. If the sources are optically thick, absorbing most other radiation from near the MBH, then the neutrino fluxes may be much higher. ANITA aims to achieve sufficient sensitivity to test either case.

Moreover, there are general and compelling reasons why neutrinos may provide the most penetrating particle messengers for not only the regions near black holes, but over much of the visible universe at very high energies. At photon energies above 10-100 TeV, the cosmic infrared background radiation itself begins to absorb and scatter even these penetrating gamma rays, and photon astronomy becomes restricted only to galactic sources. Yet we know that the high energy acceleration processes associated with ultra-energetic sources such as AGN and gamma-ray bursters extend to energies at least 7 orders of magnitude beyond this photon cutoff. If we are to fully understand massive black holes and their relationship to the ultra-high energy cosmic rays we will need direct detection and characterization of the high energy Greisen-Zatsepin-Kuzmin (GZK [5, 6]) neutrinos that are predicted to be strongly correlated to them [7].

ANITA also has a unique opportunity to constrain black hole phenomenology in inner space, via a process now understood to be well within the realm of possibility in current particle physics models. If spacetime itself consists of macroscopic hidden dimensions beyond the
3 spatial and 1 temporal that we know [8, 9], an immediate and plausible consequence of this geometry on particle physics is the opportunity for production of black hole states in high energy particle interactions [10, 11], a possibility that has generated intense interest in the CERN Large Hadron Collider, which will begin operation late this decade and could produce such states in hadron collisions [12, 13].

The presence of the almost certain GZK neutrino background from high energy cosmic ray collisions with the cosmic microwave background radiation in intergalactic space could lead to interactions in Antarctic ice in which a neutrino could produce a black hole of a mass equal to that of several thousand atoms [14, 15]. Such a microscopic black hole is highly unstable to Hawking radiation and will immediately decay in a spectacular shower of particles. Detection of such events, for which ANITA will have sensitivity far beyond any earth-based accelerator, would be a stunning and profound confirmation of a process that will have wide-ranging physics and astrophysics implications.

ANITA, as an Antarctic long-duration balloon flight, will synoptically observe the Antarctic ice sheet out to a horizon approaching 700 km, giving a neutrino detection volume of order $10^6$ km$^3$. ANITA will search for radio pulses that arise from electromagnetic cascade interactions of the high energy neutrinos within the ice. Such radio pulses, recently confirmed in accelerator experiments, easily propagate through the ice due to its remarkable radio
transparency. Fig. 1 gives a schematic view of the concept of ANITA, indicating the basic geometry for the coherent Cherenkov radio pulse produced by the cascades in Antarctic ice, and the synoptic view of the balloon payload.

ANITA will act as a pathfinding mission for high energy neutrino astronomy, because it will achieve extremely high sensitivity in a relatively short time frame. The mission will provide an early view of the potential neutrino fluxes from many possible sources. Because neutrinos can escape freely from sources in which all other forms of radiation can be heavily absorbed, ANITA will be sensitive to energy from astrophysical objects that may not be observable in any other way.

Fig. 1 shows a plot of various neutrino models, limits, and the estimated sensitivity of ANITA for the baseline 3 LDB flights. ANITA will achieve a remarkable 2-3 order of magnitude improvement over existing limits on neutrino fluxes in the energy regime it explores. We stress that the GZK neutrino fluxes shown which ANITA begins to significantly detect on this timescale are predictions of great importance to both high energy physics and our understanding of cosmic-ray production and propagation. A non-detection of these fluxes by ANITA would itself be a breakthrough which would shake several foundational theories in this field.

In addition, any instrument which achieves such a significant increase in sensitivity over prior missions has great potential for discovery, and the predictions of AGN neutrino fluxes would produce unmistakable signatures in ANITA data. Despite the small statistics of the event numbers discussed here, even a handful of events can be considered a significant detection in this field. For example, both the RICE and GLUE experiments have convincingly demonstrated rejection of anthropogenic backgrounds to a level where their limits are based on zero candidate signal events, with thermal noise and other calibration signals ensuring their instruments’ realtime sensitivity. Although ANITA does not have the atmospheric neutrino “noise” of the lower-energy neutrino detectors such as AMANDA with which to calibrate its sensitivity, the very lack of any known terrestrial or cosmic-ray physics background is also what will give ANITA its power as a neutrino observatory.

Given the high difficulty and cost of instrumenting even a small portion of the effective observed fiducial volume that ANITA can monitor, our proposed mission is a fraction of the cost of large ground-based neutrino observatories now planned. ANITA is an extremely cost effective approach toward a difficult but scientifically compelling problem.

As a pathfinding mission with high sensitivity but only modest resolution and precision, ANITA will by no means displace the need for more precise tracking detectors once the fluxes are established. Rather, it enables careful and informed design of future detectors which will help to optimize their use of costly resources and ultimately enhance their science return for a relatively modest early investment.

1.1.2 Relation to Past, Current, and Future Investigations and Missions. ANITA will be the first NASA mission to directly address the problem of high energy neutrino astronomy, and as such there are no direct relations to any prior or planned NASA missions. However, there are clear scientific connections with the science goals of several planned OSS missions. At present, ANITA is approved under the NASA OSS Space Research and Technology (SR&T) program in Particle Astrophysics. In proposing to the SMEX program, the ANITA team seeks to lower the mission risk, significantly improve the quality of this technically challenging instrument, and thus significantly elevate the science return to NASA OSS.

Because AGN massive black hole accretion disks are one of the most probable non-cosmogenic sources of ultra-high energy neutrinos, ANITA will provide information
and constraints on black hole physics that are complementary to measurements for both Constellation-X and LISA. For example, if ANITA detects a strong flux of diffuse background neutrinos with AGN characteristics, it might imply a large population of optically thick sources, and first-order measurements of the neutrino energy spectrum could suggest the population density, a measurement which would have direct relevance to estimates of source strengths and spectra for both Constellation-X and LISA. If gamma-ray bursters produce intense hadronic acceleration and are also associated with the formation of a black hole, detection of associated neutrino bursts, could significantly constrain the nature of the burst energetics.

ANITA has direct relevance to one NASA OSS mission presently under conceptual study: the Optical Wide-area Light collectors (OWL) mission [16]. OWL would fly one or more spacecraft in low-earth orbit to sense the nitrogen fluorescence emission from high energy cosmic ray air showers and neutrinos above $10^{20}$ eV. Each spacecraft employs a large optical telescope with a 1 sr field of view, and a photon-counting focal plane able to sense both position and time-of-arrival of the photons, thus yielding a 3-dimensional image of the shower. At LEO altitudes, OWL can have an effective aperture of order $10^7$ km$^2$ sr, although its duty cycle will be limited to of order 10% in the same way that ground-based fluorescence detectors are limited.

OWL has an important pre-cursor mission that is presently in phase-A study for deployment in 2008 on the Columbus module of the International Space Station, funded by the European Space Agency. This mission, known as Extreme Universe Space Observatory (EUSO) [17] involves an Italian-Japanese-US collaboration, and may have a NASA contribution through a Mission of Opportunity now in Phase A study. EUSO is basically a single-spacecraft version of OWL, although with smaller optics and effective aperture. Its energy threshold is comparable to OWL, however, since the ISS orbit is lower than that planned for OWL.

ANITA is of great importance to both of these missions. Measurements of the GZK neutrino flux will be particularly sensitive to the cut-off energy associated with the GZK process. If the results suggest a strong super-GZK component of cosmic-ray events, it would help to provide more compelling arguments that these missions are not only likely to succeed, but will achieve high resolution measurements of the super-GZK spectrum. If the results suggest that the spectrum steepens above the GZK energy, it would be a compelling reason to put effort into lowering the energy threshold, and perhaps sharpening the angular resolution in an effort to resolve the potentially nearby sources of the cosmic rays in the vicinity of the GZK cutoff.

1.1.3 Basis for ANITA.

1.1.3.1 Theoretical Basis. The concept of detecting high energy particles through the coherent radio emission from the cascade they produce can be traced back nearly 40 years to Askaryan [18], who argued persuasively for the presence of strong coherent radio emission from these cascades, and even suggested that any large volume of radio-transparent dielectric, such as an ice sheet, a geologic saltbed, or the lunar regolith could provide the target material for such interactions and radio emission. In fact all of these approaches are now being pursued [19, 45, 46].

Although significant early efforts were successful in detecting radio emission from high energy particle cascades in the earth’s atmosphere [21], it is important to emphasize that the cascade radio emission that ANITA detects is unrelatable to air shower radio emission. Particle cascades induced by neutrinos in Antarctic ice are very compact, consisting of a “plug” of charged particles several cm in diameter and $\sim 1$ cm thick, which develops at the speed of light over a distance of several m from the vertex of the neutrino interaction before dissipating
into residual ionization in the ice. The resulting radio emission is pure coherent Cherenkov radiation with a particularly clean and simple geometry, providing a high information content in the detected pulses. In contrast, the radio emission from air showers is a complex phenomenon entangled with geomagnetic and near field effects, leading to destructive interference in the detected signal. Attempts to understand and exploit this form of air shower emission have been frustrated by this complexity since its discovery in the mid-1960’s.

Surprisingly little work was done on Askaryan’s suggestions that solids such as ice could be important media for detection until the mid-1980’s, when Markov & Zheleznykh [49] revisited these ideas and confirmed the theoretical basis. More recently Zheleznykh [50], Dagkesamansky & Zheleznykh [51], Zas, Halzen, & Stanev [52], and Alvarez-Muñiz & Zas [53] have taken up these suggestions again and have confirmed the basic results through more detailed analysis. Of greater significance, a set of experiments at the Stanford Linear Accelerator center have clearly confirmed the effect and explored it in significant detail.

**Energy Threshold & Sensitivity.** The coherent radio Cherenkov emission in a particle cascade arises from the ~ 20% electron excess in the shower, which is itself produced primarily by Compton scattering and positron annihilation in flight. For a cascade of energy $E_c$, the total numbers of electrons and positrons $N_{e^+e^-}$ near shower maximum is of order the cascade energy expressed in GeV, or

$$N_{e^+e^-} \approx \frac{E_c}{1 \text{ GeV}} \tag{1}$$

which, for $E_c = 10^{18}$ eV, gives $N_{e^+e^-} \sim 10^9$. The radiating charge excess is then of order $N_{ex} \sim 0.2 N_{e^+e^-}$. Single-charged-particle Cherenkov radiation gives a total radiated energy, for tracklength $L$ over a frequency band from $\nu_{\text{min}}$ to $\nu_{\text{max}}$, of:

$$w = \left( \frac{\pi h}{c \alpha} \right) L \left( 1 - \frac{1}{n^2 \beta^2} \right) \left( \nu_{\text{max}}^2 - \nu_{\text{min}}^2 \right) \tag{2}$$

where $\alpha \simeq 1/137$ is the fine structure constant, $h$ and $c$ are Planck’s constant and the speed of light, and $n$ and $\beta$ are the medium dielectric constant, and the particle velocity relative to $c$, respectively. For a collection of $N$ charged particles radiating coherently (e.g., with mean spacing small compared to the mean radiated wavelength), the total energy will be $W_{\text{tot}} = N^2 w$. In solid dielectrics with density comparable to ice or silica sand, cascade particle bunch is compact, with transverse dimensions of several cm, and longitudinal dimensions of order 1 cm. Thus coherence will obtain up to several GHz or more.

For a $10^{18}$ eV cascade, $N_{ex} \simeq 2 \times 10^8$, and $L \simeq 6$ m in the vicinity of shower maximum in a medium of density $\sim 0.9$ with $n \sim 1.8$ as in Antarctic ice. Taking the mean radio frequency to be 0.6 GHz with a bandwidth of 600 MHz, the net radiated energy is $W_{\text{tot}} = 6 \times 10^{-9}$ J, a fraction $3.6 \times 10^{-8}$ of the total energy of the cascade. This energy is emitted into a restricted solid angle defined by the Cherenkov cone at an angle $\theta_c$ defined by $\cos \theta_c = (n \beta)^{-1}$, and a width determined (primarily from diffraction considerations) by $\Delta \theta_c \simeq c \sin \theta_c / (\nu L)$. The implied total solid angle of emittance is $\Omega_c \simeq 2\pi \Delta \theta_c \sin \theta_c = 0.36$ sr.

Since the pulse is produced by coherent superposition of the amplitudes of the Cherenkov radiation, it is completely band-limited over the specified frequency range and excites a single temporal mode of the receiver, with characteristic time $\Delta t = (\Delta \nu)^{-1}$, or about 1.6 ns in our case here. Radio source intensity in radio astronomy is typically expressed in terms of the flux density Jansky (Jy), where 1 Jy = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$. The energy per unit solid angle derived above, $W_{\text{tot}}/\Omega_c = 1.67 \times 10^{-8}$ J/sr in a 600 MHz bandwidth, produces a peak flux
density of $S_c = 4.6 \times 10^6$ Jy at a distance of 600 km.

The sensitivity of a radio telescope is determined by its size and the thermal noise background, called the system temperature $T_{sys}$. The rms level of fluctuations in this thermal noise is given by

$$\Delta S = \frac{k T_{sys}}{A_{eff} \sqrt{\Delta t \Delta \nu}} \text{ W m}^{-2} \text{ Hz}^{-1} \quad (3)$$

where $k$ is Boltzmann’s constant and $A_{eff}$ is the effective area of the antenna, including beam illumination efficiency (typically $\sim 0.6$). Note that in our case, because the pulse is band-limited, the term $\sqrt{\Delta t \Delta \nu} = 1$. For ANITA, we expect a single onboard antenna to have an effective area of $0.25 \text{ m}^2$ at 600 MHz. For observations of ice the system temperature is dominated by the ice thermal emissivity with $T_{sys} \leq 250$ K (assuming $\sim 80$ K amplifier noise figure). The implied rms noise level is thus $\Delta S = 1.6 \times 10^6$ Jy. These simple arguments show that the expected threshold for cascade detection is of order $10^{18}$ eV even to the edges of the observed area viewed by ANITA.

Using a detailed Monte Carlo simulation which deals more rigorously with the effects of neutrino propagation and interaction, and the geometric effects of refraction and detector response, we find that the flux sensitivity is comparable to the first-order estimate above. Detected pulses from this simulation are plotted in Fig. 2, showing the pulse shape for a 1 EeV cascade detected at a distance of 600 km, with an assumed system noise temperature of 280 K. In this event, at least 9 of the 36 antennas in the array detected the pulse, allowing for geolocation of the pulse origin via the gradient in the amplitude and phase.

**Minimum Detectable Flux.** The minimum detectable flux at a given energy will depend on the total fiducial volume observed by ANITA, the neutrino cross section at the given energy, the intensity distribution of the source, the acceptance solid angle of the detector(fiducial volume, the rate of background events, and the total time of observations. Since the highest flux models for neutrino fluxes predict an isotropic intensity distribution, we assume this case in our proposal. The observed volume at any given point along the ANITA flight path will depend on the altitude, depth of ice, and ice transparency.

Typically the observed volume to 0.5 km depth at an altitude of 37 km is $\sim 0.7 \times 10^6$ km$^3$ water equivalent ($\rho \approx 0.9$ gm cm$^{-3}$ for polar ice). At a neutrino energy of $5 \times 10^{18}$ eV, which will on average produce a $10^{18}$ eV cascade after accounting for inelasticity, the neutrino cross section has risen to the point where only relatively short ($\leq 300$ km) chords through the earth’s crust are still allowed. This effective restriction in upcoming angles for the neutrino produces a corresponding restriction in event nadir angles as observed at the detector, although somewhat relaxed by refraction through
the surface. At $5 \times 10^{18}$ eV only about half of the total volume in the field of view yields detectable events, and most of these are nearer the horizon.

For a given volume element near the surface, the emission solid angle which survives total internal reflection is of order 10-20% of the original 0.36 sr. Accounting for transmission losses through the ice and local surface, and beam efficiency at the detector, the average acceptance solid angle per volume element is reduced to $\leq 10^{-2}$ sr at this energy. The effective volumetric aperture is thus $\sim 3000$ km$^3$ sr w.e. at $E_{\nu} = 5$ EeV. Using an average total neutrino cross section at this energy of $\sigma_{\nu} = 0.34 \times 10^{-31}$ cm$^2$ per nucleon, the minimum detectable flux in 10 days observing time is $MDF = 2 \times 10^{-17}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This result assumes no physics background, which is a plausible assumption at these high energies. The range of predicted fluxes for GZK neutrinos above 5 EeV is $0.8 - 4.0 \times 10^{-17}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, indicating that ANITA could begin to detect such fluxes within a single flight.

### Table 1: Predicted event numbers from various neutrino models for different ANITA flight times, with 75% of flight time over deep ($\geq 1$ km) ice assumed.

<table>
<thead>
<tr>
<th>Exposure: Model</th>
<th>15 days</th>
<th>45 days</th>
<th>100 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>GZK $\nu$, min [7]</td>
<td>1.5</td>
<td>4.5</td>
<td>10</td>
</tr>
<tr>
<td>GZK $\nu$, max [24]</td>
<td>6</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td>AGN $\nu$, min [24]</td>
<td>9</td>
<td>27</td>
<td>60</td>
</tr>
<tr>
<td>AGN $\nu$, max [2]</td>
<td>20</td>
<td>60</td>
<td>130</td>
</tr>
<tr>
<td>TD $\nu$, min [26]</td>
<td>2.3</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>TD $\nu$, max [25]</td>
<td>285</td>
<td>855</td>
<td>1800</td>
</tr>
</tbody>
</table>

The results of this simulation are used earlier to plot the sensitivity levels in Fig. 1. In Table 1 we list the event numbers for various neutrino models which provide upper and lower bounds around the selected models shown in Fig. 1. These are estimated for a single flight of average duration (15 days), for the full 3-flight mission (about 45 days exposure), and for the case of 3 maximal length flights totaling 100 days. All of the estimates assume 75% exposure over ice, and the sensitivity of ANITA in these cases is sufficient to constrain all of the proposed neutrino models. Although the event numbers are small in several cases, these totals compare very favorably with estimates for existing or planned ground-based neutrino detectors, and will suffice to produce the first significant constraints on these models.

**Comparison to Ground-based Neutrino Observatories.** Several large scale ground-based high energy neutrino observatories are now operating or in construction or advanced planning stages. Among these are the Antarctic Muon and Neutrino Detector Array (AMANDA) [54], now operating for several years at a depth of 1-2.5 km in the ice at the South Pole; and the ANTARES [55] and NESTOR [56] arrays, which are in construction at depths of several km in the Mediterranean sea. A larger planned array is the IceCube project [57], which will build upon the AMANDA concept with a goal of achieving of order 1 km$^3$ of instrumented volume in the ice, optimized for an energy range from 10 TeV up to 10 PeV, at a cost of up to $240M and scheduled full operation in 2010.

All of these systems detect optical Cherenkov emission from the secondary muons produced in the same neutrino interactions that initiate the electromagnetic cascades that ANITA will detect. These muons have ranges of up to tens of km, and detectors such as AMANDA can thus detect a neutrino interaction at significant distances from the vertex of the interaction by tracking the resulting muon, which follows the direction of the original neutrino. This approach yields high angular precision and is the most cost-effective approach to detection of neutrinos from TeV to PeV energies. The effective volume of a
cubic km instrumented detector which uses the muon tracking approach is thus extended to roughly the product of the cross-sectional area of the detector times the muon range, which varies from several km in ice at TeV energies to several tens of km at EeV energies, where it flattens out [57].

Because of this saturation of the muon range at EeV energies, the effective volume of a muon tracking array also saturates at these energies. For the planned cubic km array IceCube, this implies an effective neutrino aperture of order $30 \text{ km}^3 \text{ sr}$ at 1 EeV, about an order of magnitude less than ANITA at the same energy. Thus the muon tracking system matches a 45 day ANITA exposure after of order 1.5 years of effective exposure time, also known as live-time.

At 10 EeV, however, the muon tracking array effective volume has increased only slightly (due mainly to increased muon detection efficiency) but the ANITA volume has increased by another order of magnitude due to the quadratic rise of radio emission power from the Askaryan effect. The muon tracking array now requires more than a decade to match the ANITA 45 day livetime. This brief comparison thus illustrates the power and cost-effectiveness of the ANITA approach for EeV neutrino detection.

1.1.3.2 Experimental basis: Accelerator Measurements. Although it is not presently possible to produce EeV cascades in terrestrial accelerators, electromagnetic showers with composite total energies in this range can be easily synthesized by superposing gamma-rays of energies above the pair-production threshold. If the gamma-ray bunch is small compared to the wavelength of the radio emission (true for most pulsed linacs), the resulting showers will differ from natural EeV showers only logarithmically, due to the details of the initial interaction. However, since the bulk of the radio emission arises from the region of maximum shower development, the differences in radio Cherenkov emission are modest and easily quantified.

Two of the investigators on the team (Gorham and Saltzberg) have performed three experiments along these lines, the first at the Argonne Wakefield Accelerator (AWA) in the fall of 1999 [58], and more recently at the Stanford Linear Accelerator Center (SLAC) in the summer of 2000 [59] and 2002 [44]. Because of the importance of these measurements with respect to the ANITA effort, we digress here to discuss these in some detail, focusing on the later, more complete experiments at SLAC.

SLAC experiments. The cascades used in this experiment were initiated by intense bunches of pulsed gamma-rays. The gamma-rays were produced via bremsstrahlung from the primary electrons in the linac. In the discovery experiment, a large silica sand target and antennas were placed in a gamma-ray beamline in the Final Focus Test Beam facility at SLAC in August 2000. The apparatus was placed 30 m downstream of bremsstrahlung radiators that produced a high-energy photon beam from 28.5 GeV electrons. The results from this discovery experiment have been published recently in Physical Review Letters [59], to which we refer the reader for more details.

In the 2000 experiment the dielectric-filled target was a $1 \times 1 \times 4 \text{ m}$ container built largely from non-conductive materials such as wood and plastic which was filled with 3200 kg of dry silica sand. The sand target was rectangular in cross section perpendicular to the beam axis, but the vertical faces on both sides were angled to facilitate transmission of radiation arriving at the Cherenkov angle (about $51^\circ$ in silica sand at microwave frequencies). In the 2002 follow-on experiment, the sand was replaced by synthetic rock salt, which has a higher dielectric constant and lower loss tangent than silica sand.

Fig. 3 (top) shows a typical pulse profile (inset) and a set of measured peak field strengths for pulses taken at different points along the shower in the 2000 experiment. The plotted curve shows the expected profile of the to-
Figure 3: Top: Shower RF field strength profile with typical pulse (inset). Middle: Polarization measurements of a typical RF Cherenkov pulse at 2 GHz. Bottom: Correlation of plane of polarization with antenna offset from shower axis.

Pulse polarization was measured with an S-band (2 GHz) horn directed at a shower position 0.5 m past the shower maximum. Fig. 3 (middle) shows the pulse profile for both the 0° and 90° (cross-polarized) orientations of the horn. The lower two panes of this portion show the derived degree of linear polarization and the angle of the plane of polarization, respectively. Because of the vector correlation of the pulse polarization with the shower velocity vector and the Poynting flux vector, it is possible to use the angle of the polarization to track the shower axis. An example of this is shown in Fig. 3 (bottom), where the angle of the plane of polarization is plotted at three locations with respect to the shower axis, showing the high correlation with the predicted angle. This feature of radio Cherenkov emission will help to improve ANITA’s ability to reconstruct the shower axis without the usual triangulation methods used in optical ring-imaging Cherenkov detectors, which do not measure the polarization.

Fig. 4 (top, left pane) shows a typical sequence of pulse field strengths versus the total shower energy, which was varied both by changing the beam current and the thickness of the bremsstrahlung radiators. The fitted linear rise of field strength with beam current is consistent with complete coherence of the radiation, implying the characteristic quadratic rise in the corresponding pulse power with shower energy. The lower half of Fig. 4 shows a similar result for the 2002 experiment, but now covering a much wider range of energy, plotted as pulse power instead of field strength. The Askaryan...
process is found to be quadratic over four orders of magnitude in shower energy—covering precisely the range of interest for ANITA.

Fig. 4 (top, right pane) shows the spectral dependence of the radiation, which is consistent with the linear rise with frequency that is also characteristic of Cherenkov radiation. Also shown is a curve based on a parameterization of Monte Carlo results [52]. The uncertainties are estimates of the combined systematic and statistical uncertainties. Note that the figure compares absolute field strength measurements to the predictions and the agreement is very good.

In summary, there is clear experimental evidence that Askaryan’s hypothesis is confirmed and that the predicted emission from high energy cascades is present in the expected amounts. This lends strong support to experiments, including ANITA, designed to exploit this effect for high energy neutrino and cosmic ray detection.

Figure 4: *Top left:* Coherence of RF Cherenkov at 2 GHz, measured during 2000 SLAC experiment. *Top right:* absolute field strength and prediction from Cherenkov. *Bottom:* Coherence of radiated power over the 0.2-1.2 GHz band.

Figure 5: *Field attenuation lengths in ice as a function of temperature and frequency [48].*

1.1.3.3 Experimental Basis: Related experiments.

RICE. The Radio Ice Cherenkov Experiment (RICE) [45] functions as a subelement of the larger AMANDA array. AMANDA, for which one of the ANITA co-investigators (S. Barwick) is the spokesman, is the first high energy neutrino telescope to operate effectively in the TeV to PeV energy range, and has demonstrated the effectiveness of precision embedded tracking Cherenkov arrays for these energies.
RICE forms a subarray of antennas in a volume above the main optical array, about 250-400 m deep in the ice, along the AMANDA supply cables. RICE is among the first experiments to attempt to exploit the Askaryan effect and has demonstrated that the noise levels in the upper layers of the ice are consistent with ambient thermal noise. RICE extends the reach of AMANDA up to EeV energies, although it is probably too small at present to achieve limits which can constrain GZK neutrinos in the near future. The most relevant aspects of RICE to ANITA are measurements of the attenuation length of the ice over a bandpass that matches fairly well with ANITA. RICE finds a lower limit on the attenuation length in this band of at least 500 m.

**Antarctic radar.** For many years radar techniques have been used with great success to map out the Antarctic land masses beneath the ice, even at depths of more than 3 km. The attenuation length in ice is found to have a strong dependence on temperature, with attenuation increasing rapidly as the ice approaches its melting temperature. In general, this is only important in the coastal glaciers or near the bottom of the ice sheets where the ice is affected by coupling to the underlying land mass. In Fig. 5 we show several curves of the attenuation length for different temperatures for typical Antarctic sheet ice, with extrapolations to higher frequencies.

Typical temperatures in the deep polar ice sheets are cold, with average temperatures in the upper 1.5 km measured to be below $-50^\circ$ at Vostok station [48] with little variation. Nearer the coast in the shallower portions of the sheet, measurements of the average temperature of the entire sheet down to $\sim 1$ km give $-30^\circ$. It is thus evident that radio propagation in the ice over most of the Antarctic ice sheet should exceed several hundred m attenuation length, and in the deeper ice sheets approaches 1 km attenuation lengths, particularly at the lower frequencies.

**RF noise.** In January of this year, ANITA personnel were able deploy a broadband, ANITA-like, dual-polarized antenna system at the South Pole station in several locations, in one case at a distance of 6.6 km from the station in a ski hut. In this effort, dubbed the South Pole Impulsive Noise (SPIN) experiment, low-noise receiver system was used to record ambient thermal and impulsive backgrounds over a several hour period at each location. While the noise near the station was fairly high as expected, once
the SPIN location was moved out to the ski hut, the impulsive backgrounds found in this experiment became very low—in fact, in only one period, just after 4 p.m. local time when a satellite uplink from the South Pole station became active, were any significant impulsive triggers seen at all. Since, next to McMurdo station, the South Pole station is the most active during austral summer, these results provide strong evidence that ANITA will operate in low-noise conditions.

In addition to impulsive triggers, the SPIN experiment measured ambient thermal noise levels, including both the underlying ice and the solar spectrum, over the frequency range from 0.2-1.2 GHz. The results of this are shown in Fig. 6, where both the derived ice and solar spectra are shown. Despite some probable residual calibration uncertainty in the shape of the ice spectrum, both are consistent with ambient noise at the thermal floor as predicted, and these measurements lend further support to the ANITA sensitivity estimates.

GLUE. The GLUE experiment [19], a collaboration of JPL and UCLA, utilizes two spacecraft telecommunications radio telescopes in the Goldstone facility of the NASA Deep Space Network to observe the lunar regolith in search of radio pulses from cascades in the energy region above $10^{20}$ eV. GLUE bears many similarities in the technique to ANITA. For example, multiple antennas, polarizations, and frequency bands are used to isolate the desired signal pulses from any terrestrial or other background interference. In both experiments the effective detection volume arises from synoptic observations of a large spatial region, with radio pulses originating within the material (regolith or ice) below the observed surface.

Many of the present design concepts in the ANITA RF processing can be traced to techniques that have been perfected by several of the proposers for the GLUE project. In particular this applies to the development of approaches which optimize the detection and recognition of band-limited, polarized pulses. This experience is especially valuable in terms of recognition and mitigation of radio frequency interference which is a ubiquitous problem in all of radio astronomy.

To date, GLUE has set only limits in the energy regime it explores, based on a first pass conservative analysis of the data, with no pulse events surviving the cuts for the first 50 hours of live-time.

1.1.3.4 FORTE: A Space-Based precursor of ANITA. The Fast On-orbit Recording of Transient Events (FORTE) satellite [65], launched in August 1997, was designed and built through a collaborative effort of Los Alamos National Laboratory and Sandia Laboratory, with a primary goal of studying impulsive optical and radio transients that may be relevant to international nuclear treaty verification. The mission is non-classified and has a strong atmospheric physics program in studies of lightning and related upper atmosphere and ionospheric events. The satellite was launched into a nearly circular orbit at 800 km altitude and 70° inclination.

The system has recorded over $4 \times 10^6$ impulsive transient events, including new forms of lightning, and may in fact also be sensitive to radio emission from giant cosmic ray air showers. Fig. 7 shows global VHF noise levels recorded by FORTE in two bands between 30-40 MHz. It is significant that some of the lowest recorded levels appear over the Southern Ocean and along the Antarctic coast. This latter fact is of importance to ANITA, since a majority of the anthropogenic noise sources in Antarctica are in coastal camps. The fact that FORTE observes RF noise consistent with Galactic thermal noise levels is encouraging for ANITA, since interference in the 30-50 MHz band is usually much higher than in the bands of interest for ANITA.

FORTE provides an excellent example of the ability of a synoptic antenna to operate effectively in the presence of noise over a wide ra-
Figure 7: A FORTE compilation of global VHF noise levels, in mV per m per MHz (1 mV/m = 2.6 nW/m²), as observed from an 800 km altitude. The lowest levels (green) are consistent with Galactic background noise, and occur in the Southern Ocean and along the Antarctic coast.

dio bandwidth, and demonstrates that systems which seek to isolate specific impulsive events from a wide variety of anthropogenic noise can operate quite effectively.

FORTE can in principle trigger on neutrino-induced EMP events, but because of its much higher altitude and more limited frequency range, FORTE’s energy threshold is much higher than that of ANITA. This ability has been recently exploited in analysis by N. Lehtinen [68] who analyzed 3.7 days of FORTE live-time over the Greenland ice sheet and was able to reject all but two of the observed impulsive triggers, and thus set a strong upper limit on the flux of neutrinos in the 10²² eV range, well above most of the flux models of interest for ANITA, but still able to constrain the Z-burst model for high energy cosmic rays.

1.1.4 Baseline Mission Overview. ANITA will make use of radio emission from the secondary electromagnetic cascade induced by a neutrino interaction within the polar ice sheet to detect neutrino events anywhere within a million square km area viewed by the instrument from the 37 km altitude of the balloon. The remarkable transparency of Antarctic ice to radio waves makes this experiment possible, and the enormous volume of ice that can be simultaneously monitored leads to an unparalleled sensitivity to neutrinos in the energy range of 0.1 to 100 EeV.

ANITA will obtain a total of 45 days live-time during our baseline mission. A conservative approach has been adopted toward achieving the planned 45 day live-time, basing this total on 3 Antarctic flights, each of which achieves an average of 15 days of live-time. Clearly a more cost-effective approach will be to make use of multiple orbits around the pole if possible; this has now been demonstrated in the remarkable 31.8-day flight of the Trans Iron Galactic Recorder (TIGER) payload in the 2001/2002 season. We anticipate that a live-time approaching 100 days is possible with three ANITA flights under optimal conditions.

During the flight, ANITA will maintain a nominal altitude of 37 km; however, loss of even up to 10 km of altitude would not constitute mission failure unless the balloon flight path did not remain over the ice sheet. The reason for this is
that a lower altitude and the corresponding loss of viewed volume of ice is compensated for by increased sensitivity at lower energies.

1.1.5 Measurements and Analysis Approach. ANITA will provide measured geolocated positions, estimated energy, and derived track direction in celestial coordinates for a set of candidate neutrino-induced cascades above an energy of about $3 \times 10^{17}$ eV. The basic analysis approach will be to establish a matched-filter type of template for rejection of all spurious interference and thermal noise triggers, based on models and instrument calibration data. ANITA is unusual for a NASA astrophysics mission because the expected numbers of detected events from neutrino EMP within the ice is far smaller than that due to background, and background rejection will be fundamental to all data analysis. We anticipate background rejection factors of order $10^4$, based on our experience achieving background rejection factors 1-2 orders of magnitude higher in high energy physics experiments, upon which much of the ANITA hardware and trigger logic is based.

If no candidate events are confirmed, careful estimates of the sensitivity from the on-orbit calibration, combined with the science team’s ice properties and topography studies, will be used to derive a firm upper limit to the flux density of the neutrinos in this energy regime. This is done by estimating the effective fiducial volume of the observed ice over the actual balloon track, and combining this with the antenna and trigger efficiency and collecting area. The methods to do this have been proven in the team’s extensive experience with other neutrino detectors of all kinds.

1.1.6 Data products & Science Results. The raw data products produced by ANITA are the detected events themselves, sorted into quality groups according to the likelihood that they originate from a neutrino cascade. This raw data archive will form the basis for a processed set of neutrino candidates for which the science team will determine the best-fit energy of the cascade, and the direction of the original neutrino that caused it. The resulting sky map and energy distribution of neutrino events can then be analyzed for the properties of the parent source population, analogous to the way that significant information about the sources of Gamma-ray Burst events was determined prior to direct identification of the sources. In ANITA’s case, however, we stress a compelling detection of the neutrino events would itself be a powerful scientific event, providing the bulk of the scientific justification. The energy and angular information then adds further significant value and refinement to the results. These goals and their relation to the measurement, instrument, and mission requirements, are outlined in Table 2.

1.1.7 Quality and Quantity of Data to be Returned. Table 3 summarizes the main data quality capabilities we expect for ANITA cascade radio pulse measurements. As we shall describe below, we expect the instrument to provide a randomly triggered noise sample for all antennas about once per minute during the total flight time. The rates for actual neutrino events are expected to be as low as several events in 45 days, or as high as several thousand. In any case the bulk of the data set will consist of an extensive archive of about $3 \times 10^4$ noise sample events, each of order several tens of Kbyte, and a subsample of processed candidate events. The net size of the archive is estimated to be less than 10 Gbyte.

1.2 Science Implementation. One of the key features of our science implementation is the plan to build two identical complete instrument/gondola packages, to insure readiness of the balloon payload in successive flight years. Balloon payloads cannot normally be recovered and refurbished in time to fly in successive years. Because of the high science value of a quasi-continuous yearly data stream, and the higher level of efficiency that has been demon-
Table 2: Science traceability matrix for ANITA objectives, data products and science results.

<table>
<thead>
<tr>
<th>Detailed Science Objectives &amp; Expected Results</th>
<th>Scientific Measurement Requirements</th>
<th>Instrument Functional Requirements</th>
<th>Mission Functional Requirements (top level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GZK neutrino detection.</td>
<td>Achieve 300K thermal noise limit. Distinguish EMP from background. Observe max. ice volume</td>
<td>Antenna/rcvr T &lt; 80K. [ \geq 1 \text{ GHz spectral range} ] Dual-polarization data. 2( \pi ) antenna array. Altitude \geq 30 \text{ km}.</td>
<td>T &lt; 250K ambient. EMI avoidance. Ground/flight calibration. Flight path over ice. 45 days total flight time.</td>
</tr>
<tr>
<td>0.1-100 EeV neutrino spectrum.</td>
<td>[ \Delta E/E \leq 1 ] High linearity/dynamic range. \leq 50% range resolution.</td>
<td>\leq \text{Few km geolocation.} Ice topography, temperature.</td>
<td></td>
</tr>
<tr>
<td>Low-resolution EeV neutrino Sky map.</td>
<td>15(^{\circ}) azimuth. \leq 2(^{\circ}) elevation.</td>
<td>10% Antenna gain calibration. 1 ns event timing.</td>
<td>Balloon pointing knowledge \leq 1(^{\circ}).</td>
</tr>
</tbody>
</table>

Table 3: Estimated performance capabilities of ANITA instrument for cascade measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta ) reconstruction</td>
<td>event nadir angle</td>
<td>( \approx 2^{\circ} ) at ( \theta \approx 85^{\circ} ), ( \leq 12^{\circ} )</td>
</tr>
<tr>
<td>( \phi ) reconstruction</td>
<td>azimuth using amplitude ratio based on polarization plane near horizon</td>
<td>( \sim 10^{\circ} ) error box, ( \leq 50% )</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>measured field is lower limit volumetric aperture</td>
<td>( \Delta E/E \approx 1 ), 1260 km(^3) sr</td>
</tr>
<tr>
<td>fractional range resolution</td>
<td>Thermal noise triggers</td>
<td>( \leq 0.02 \text{ Hz} )</td>
</tr>
<tr>
<td>energy uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective aperture at 3 \times 10^{18} \text{ eV}</td>
<td>288 total channels/event</td>
<td>( \sim 30 \text{ Kbyte} )</td>
</tr>
<tr>
<td>Expected trigger rate</td>
<td>10 times expected trig rate</td>
<td>10 Gbyte</td>
</tr>
<tr>
<td>Event size</td>
<td>Maximum archive size</td>
<td></td>
</tr>
</tbody>
</table>

Stratified by JPL in the past in spacecraft programs where identical paired systems were built, we have adopted this approach to maximize the science return for program cost within the cap. The impact of this approach to mission implementation is detailed in a later section.

1.2.1 Instrumentation. The ANITA instrument is fundamentally a broadband antenna cluster which is arrayed in such a way as to be optimized for pulse detection and characterization. The requirement for synoptic observation of all of the ice visible from the balloon prescribes a nearly 2\( \pi \) field of view, implying relatively low-gain antennas. This competes with the need for maximum sensitivity which otherwise dictates antennas with the highest possible gain, since the gain \( G \) and effective collecting aperture \( A_{\text{eff}} \) are related by \( A_{\text{eff}} = \frac{G \lambda^2}{4\pi} \). For ANITA, an antenna with a beamwidth that varies only slowly with frequency is preferred, so that there will be complete beam-overlap of adjacent antennas at all frequencies of interest.

1.2.1.1 Antennas. ANITA will use a dual-linearly-polarized quad-ridged horn antenna as the baseline design. Alternative antennas are under investigation, and one of the benefits of the NASA SR&T program that is presently supporting ANITA research and development is that it allows for early investigation of this critical component.

The beamwidth of the antenna chosen is about 60-70\(^{\circ}\) with a gain of approximately 10 dBi at around 300 MHz. By arranging a cylindrically symmetric array of 2 levels of 8 anten-
nas each, with a downward cant of about 10°, we achieve complete coverage of the horizon down to within 40° of the nadir, virtually all of the observable area. The antenna beams in this configuration overlap within their 3 dB points, giving redundant coverage in the horizontal plane. A second array of 16 antennas on the lower portion of the payload provides a vertical baseline for establishing pulse direction in elevation angle; an additional cluster of nadir-pointing antennas complete the total.

The frequency range for the antennas is 0.2 to 1.2 GHz. The lower limit of the range is primarily dictated by limitations of the gondola size and the requirement to have overlapping beams, and the upper end of the frequency range is set by the fact that the radio attenuation of the ice is believed to increase rapidly above 1 GHz or so. Because the EMP from a cascade is known to be highly linearly-polarized, we convert the two linear polarizations of the antenna into dual circular polarizations using standard 90° hybrid techniques. This is important since a linearly polarized pulse will produce equal amplitudes in both circular polarizations, and thus some background rejection is gained by accepting only linearly-polarized signals.

1.2.1.2 Antenna Array Geometry. Figure 8 shows that basic layout of the gondola and the antennas. There are three separate antenna clusters. The two horizon-view clusters consist of two azimuthally offset rings of 8 antennas each. The two ring clusters view to within ~40° of the nadir. A cluster of 4 antennas at the bottom of the instrument then complete the coverage at the nadir. For the two sets of ring clusters at the upper and lower portions of the gondola, the vertical offset is just under 4 m, and provides a baseline for pulse-phase interferometry of the received impulse.

Geolocation of the pulse direction is accomplished by different methods in elevation and azimuth. Elevation angle is the most important parameter for determination of the energy of a neutrino cascade, since it is directly related to range. The elevation angle resolution that can be achieved for a pair of antennas separated by baseline B is of order \( \Delta \theta \approx \lambda_{\text{min}} / (2B \sin \alpha) \), where \( \lambda_{\text{min}} \) is the shortest wavelength detected in the pulse, and \( \alpha \) is the angle of the arrival direction of the pulse with respect to the baseline. For \( \lambda_{\text{min}} = 0.3 \) m and a 3.7 m baseline, we expect \( \sim 2° \) resolution near the horizon, which corresponds to a fractional range resolution of about 50% at the horizon, improving rapidly to about 10% near the edge of the nadir field of view. For the Askaryan process the cascade energy resolution \( \Delta E/E \propto \Delta R/R \) because the detected field strength falls off as \( R^{-1} \). There is however no strong motivation to improve the energy resolution beyond this level, since there is an inherent uncertainty of this same order due to the unknown inelasticity of the original neutrino interaction. A factor of 2-3 energy uncertainty at these high energies would have little effect on the science impact of the measurements.

Azimuth angle will be determined with a coarser resolution by amplitude measurements of adjacent antennas which both detect the
pulse. The beam amplitude pattern of the antennas will be calibrated before launch to 3-5% accuracy, and this should provide resolution of about 1/5 of a beam (\(\sim 12^\circ\)) by looking at the amplitude ratio in antenna pairs.

1.2.1.3 RF Detection & Digitization System. Figure 9 shows the basic layout of the detection and digitization system for ANITA. The dual linear polarization signals from the antenna are converted to dual circular polarization by an internal hybrid (not shown) and these signals are then fed into a first stage low-noise amplifier (LNA). The LNA is not aggressively cooled, since the system noise temperature is several hundred K due to the ice in the field of view. An amplifier noise temperature of \(\leq 80\) K is assumed. Additional amplifier stages then bring the voltages up to a level appropriate for digital sampling, and the signal is split to provide for both the trigger and data recording paths.

An external Field-Programmable Gate Array (FPGA) sequences the accepted triggers. This FPGA will also be used to zero-suppress noise triggers and channels containing only noise to improve the effective telemetry bandwidth.

We estimate that a trigger based on majority logic over several antennas (as in Fig. 2 above) can achieve a threshold of order 2\(\sigma\) above the thermal noise level for each antenna. At this level the rate of accidental triggers is of order 1 every 3-4 minutes. This basic trigger rate is provides a quasi-continuous monitor of instrument health with no risk of data contamination. In fact, thermal noise triggers will not have the required characteristics to emulate the true cascade signals, for several reasons: (1) Thermal triggers will not obey spatial and temporal closure relationships among antennas. (2) Thermal noise will not be correlated between polarization channels. (3) The antenna pattern of the trigger will be random for a thermal noise trigger, and the individual antenna response functions will be uncorrelated. (4) Thermal triggers will not be able to reproduce the Cherenkov spectrum, which has a distinct phase and amplitude across the band.

Measurement of the plane of polarization of the pulse is also an important part of the available information, since for a cascade, the plane of polarization is defined by the track of the initial particle and the Poynting vector of the radiation. Thus any measurement of the polarization vector of the pulse gives direct information on the projected track direction of the incident particle. This was indicated earlier by the lower portion of Fig. 3, where such measurements were demonstrated in a SLAC experiment. The precision in radians of this measurement is of order 1/SNR per antenna. Combining signals from several antennas we expect to achieve precision of \(\leq 10^\circ\) for this measurement on each event. Combining this with the constraints on the track geometry from the other range and angle measurements should give comparable overall resolution on the absolute particle direction.

Once the trigger logic has generated a coincidence, the digitizer is enabled and all of the signals stored in the switched capacitor array (SCA) ring buffer are digitized, prioritized, and then submitted to the telemetry, which is discussed further in the mission implementation section below.

1.2.2 Baseline Mission Design. The ANITA mission is unusual for astrophysics missions in its reliance on the Antarctic ice as the Cherenkov radiator in an enormous scale of detector. The onboard antenna clusters by analogy play the role of photomultipliers in a Cherenkov or scintillation counter, by collecting the secondary emission from the medium in which the particle of interest interacts. For this reason one of the primary mission constraints is that ANITA spend as much time as possible with a field of view containing only deep ice.

Fortunately this constraint is not a major restriction for the mission, since in fact the typical flight path for a circumpolar Antarctic flight
spends 100% of its time over the ice. This is shown in Fig. 10. The plot shows the coastal boundary of Antarctic ice, and indicates the average balloon flight path by a circle that crosses McMurdo Station (the launch site). A series of fields-of-view of the balloon are indicated by the smaller circles that are centered along the flight path. On the bottom pane of the figure we show data for the average and range of depths encountered within several hundred km of the flight path. These indicate the distance to the horizon which occurs at about 680 km for a 37 km altitude. Approximately 70% of the field of view is of the ice sheet with average depth of order 2 km or more. Another 15% occurs over shallower coastal ice or over the ice shelves, with depths of several hundred meters to 1 km. The balance of the observed field of view is of the Ross and Weddell seas. The ice depth averaged over the entire flight path is 1500 m, with an estimated average temperature of -40 C, implying an average attenuation length of 0.5 km.

The average mission duration for one circumpolar flight is to date just under 15 days. We note that recent Antarctic flights are attempting to execute more than one circumpolar orbit during a mission, and flight durations in the near future are expected to approach 30 days. Our mission plan will be to take advantage of such improvements if possible, but we budget for 3 flights of 15 days each to achieve our 45 day goal.

1.2.3 Minimum Mission The minimum mission for ANITA will involve scaling back to a single Antarctic flight of assumed duration 10-15 days. Construction of a second complete instrument to enable 1 year turnaround for repeated flights in successive years would also be omitted from the mission plan. The science impact of descoping from the baseline to the minimum mission is significant, since the risk of little or no science return is significantly elevated. The flight may be aborted due to weather or instrument malfunction, and the instrument may be damaged or lost. However, if the failure risks are avoided and the mission successfully achieves at least a 10 day livetime (2/3 of the average single-LDB flight time), ANITA will still achieve significant science results in the possible detection of GZK neutrinos and im-

Figure 9: Block diagram of the ANITA detector system. One antenna sub-block is included.
Figure 10: Top: Map of Antarctic ice boundary with balloon flight path (blue) several balloon fields of view (purple), and the mean limits of the fields of view (red) shown. Bottom: a plot of the average and rms values of the ice depth along a several hundred km swath along the nominal LDB path, which begins and ends at McMurdo station. The ice depth averaged over the entire flight path is 1700 m.

important constraints on all current neutrino flux models. In this respect the minimum mission is a descope that adds risk, but does not diminish the potential science return that is possible with ANITA.

1.2.4 Data Analysis and Archiving. The data will consist of measured complex quantities for up to $3 \times 10^4$ recorded triggers in a 45 day total exposure, whether over 1 or up to three flights. Each event will consist of the direct time series of each IF channel for each polarization of each antenna that participated in the trigger, along with adjacent antennas that had geometric coverage capable of detecting some of the pulse power. Thus of order 1/3 of the antennas will be recorded for each trigger, giving 24 distinct pulse profiles, each of order 100 ns long around the recorded pulse. In addition to this each trigger will record the balloon altitude, geographic location, and UT time from GPS measurements, as well as the ambient noise levels for each antenna so that the exact threshold can be established. Telemetry constraints will prevent direct telemetry of a large cluster of triggers, but particular care will be taken to maintain the ability to record pulse pairs within several hundred microseconds of each other, since such events could be associated with tau neutrino interactions.

The ANITA team will establish two independent archive and data analysis centers among the participating institutions, one on the west coast, at either UC Irvine or UCLA, and a second at either Penn State or Bartol Research Institute with the University of Delaware. The activities and schedule for data products release for these data centers is as follows: 1. Archiving of raw data: Coincident with telemetry relay from NSBF Palestine. 2. Release of snapshot (first pass calibrated) data set: Within 3 months of receipt of telemetry. Calibration files will also be available at this time. 3. Release of fully calibrated and filtered data set and neutrino candidate event cluster: Within 6 months of receipt of telemetry. This sequence will be followed after each Antarctic flight.

1.2.5 Science Team. To conclude this section, we summarize the science team, a diverse and talented combination of ballooning experts, experimental neutrino physicists, and astrophysicists, in Table 4.
<table>
<thead>
<tr>
<th>Investigator, Institution</th>
<th>Capabilities, Experience</th>
<th>Role or responsibility</th>
<th>Source of support</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principal Investigator</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prof. P. Gorham (PI) JPL &amp; Univ. of Hawaii</td>
<td>Radio science; GLUE, Astroparticle physics</td>
<td>Science Oversight, scientific integrity</td>
<td>NASA SS¹</td>
</tr>
<tr>
<td><strong>Co-Investigators:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prof. S. Barwick UC Irvine</td>
<td>AMANDA Spokesman, Neutrino astronomy</td>
<td>Gondola development payload integration</td>
<td>NASA SS¹</td>
</tr>
<tr>
<td>Prof. J. Beatty Penn State</td>
<td>High energy Cosmic rays, Extensive ballooning</td>
<td>Gondola development; trigger &amp; data analysis</td>
<td>NASA SS¹</td>
</tr>
<tr>
<td>Prof. D. Besson Univ. of Kansas</td>
<td>RICE project, Antarctic experiments</td>
<td>RF background study, Antarctic support</td>
<td>NASA SS¹</td>
</tr>
<tr>
<td>Prof. D. Cowen Penn State</td>
<td>High energy Neutrinos, IceCube experiment</td>
<td>Realtime/offline; Software devel.</td>
<td>NASA SS¹</td>
</tr>
<tr>
<td>Prof. M. DuVernois Univ. of Minnesota</td>
<td>High Energy Cosmic rays Extensive ballooning</td>
<td>Gondola development trigger &amp; data analysis</td>
<td>NASA SS¹</td>
</tr>
<tr>
<td>Dr. K. Liewer JPL</td>
<td>Radio Science; GLUE flight project development</td>
<td>System Engineering RF configuration</td>
<td>NASA</td>
</tr>
<tr>
<td>Dr. C. Naudet JPL</td>
<td>Radio Science; GLUE Ground systems devel.</td>
<td>Code development, Ground/flight systems</td>
<td>NASA</td>
</tr>
<tr>
<td>Prof. D. Saltzberg UCLA</td>
<td>High energy physics, RF pulse measurement</td>
<td>RF pulse calibration, UCLA data archive</td>
<td>NASA SS¹</td>
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<tr>
<td>Prof. D. Seckel Univ. of Delaware</td>
<td>RICE project, Neutrino astrophysics</td>
<td>Modeling &amp; analysis, U. Del. data archive</td>
<td>NASA SS¹</td>
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<tr>
<td>Dr. G. Varner Univ. of Hawaii</td>
<td>Electronics, Detector ASIC development</td>
<td>RF&amp; Trigger hardware</td>
<td>NASA</td>
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<tr>
<td><strong>Collaborators:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dr. J. Clem Bartol Research Inst.</td>
<td>High Energy cosmic rays, hardware development</td>
<td>trigger development support</td>
<td>...</td>
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<tr>
<td>Prof. S. Coutu Penn State Univ.</td>
<td>HE Cosmic ray &amp; neutrino, Extensive ballooning</td>
<td>Gondola development; trigger &amp; data analysis</td>
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<tr>
<td>Prof. P. Evenson Univ. of Delaware</td>
<td>HE Cosmic rays Balloon &amp; payload</td>
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<tr>
<td>Prof. F. Halzen Univ. of Wisconsin</td>
<td>Neutrino astrophysics, Radio emission theory</td>
<td>Radio pulse modeling, GZK neutrino theory</td>
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<td>Prof. D. Kieda Univ. of Utah</td>
<td>GZK cosmic rays, modeling &amp; analysis</td>
<td>GZK neutrino models, neutrino spectral analysis</td>
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<tr>
<td>Prof. J. Learned Univ. of Hawaii</td>
<td>Neutrino astrophysics, Experimental techniques</td>
<td>Monte Carlo modeling, Calibration analysis</td>
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<tr>
<td>Dr. S. Matsuno Univ. of Hawaii</td>
<td>Neutrino astrophysics, Experimental techniques</td>
<td>Software Development, Trigger system</td>
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</tr>
</tbody>
</table>

(1) NASA SS indicates up to 2 months NASA Summer Salary support is requested for 9-month faculty whose research time during the regular term is supported by their institution.
2 MISSION IMPLEMENTATION

In this section we address aspects of the proposed investigation which deal with the execution of the program as a balloon mission. These include unusual requirements levied on the mission by the science goals, as well as issues in the development of the instrument which have mission implications.

2.1 General information. We have provided a mission synopsis above. Here we describe in more detail some of the specifics of the mission profile. Table 5 summarizes these, and we address them individually here.

2.1.1 Launch windows & flight duration. The National Scientific Balloon Facility (NSBF), in cooperation with the National Science Foundation (NSF), is the managing organization for Antarctic balloon flights. The balloon launch window in Antarctica is constrained by the need to conduct operations in austral summer, and the NSBF indicates a launch window running from Dec. 1 to completion of the mission by Feb. 1. We propose our first flight for the 2006-2007 window. Typical Antarctic LDB flights average about 15 days in duration, with multiple circuits possible with permission from NSBF.

2.1.2 Allowed Altitude and Latitude Range. Under normal conditions the altitude for an Antarctic balloon varies between 35-40 km. For most balloon missions, this is a critical parameter since the balloon is used to elevate the payload above the atmospheric overburden. In the case of ANITA, the atmosphere is irrelevant, and the balloon elevation provides the synoptic viewing area. Thus, although we are assuming nominal flight altitudes in our estimates of the mission sensitivity, the science return is not a strong function of altitude.

In contrast, the range of latitude covered in the flight is of significance, since a flight path that fails to remain over the ice for most of the mission will reduce the observing efficiency. However, under normal launch conditions, wind patterns ensure that the flight path remains between 73-82° S, with a high probability that it remains close to the launch latitude of McMurdo station at 78° S. A flight path which strays north below 75° S will begin to lose some effective observed volume of ice, but even a flight path that circuits the extreme northern limits of the range above will retain 50-60% of its observed ice volume. Anomalies in the flight path may thus produce some degradation of mission goals but not a mission failure.

2.2 Telemetry. The highest link bandwidth presently available for Antarctic flights is the TDRSS link at 6 Kbits/s. The SMEX AO has indicated the planned availability of a higher bandwidth TDRSS channel through use of a High Gain Antenna (HGA). For the purposes of this proposal we take a conservative approach in using the standard TDRSS link, but the availability of the HGA will potentially add significant improvements to ANITA’s risk profile and science return.

For each trigger we sample all of the antennas to ensure collecting all possible information. We thus have 36 antennas with 2 polarization channels each, giving 72 channels to be sampled. The sample rate is 2.5 Gsamples/s, and we record 100 ns per channel with 12-bit resolution, giving of order 30 Kbyte per event, including ancillary data. Thus a selected trigger rate of 1 event per minute can be supported with a 50% link margin remaining; this is well above the ambient thermal noise trigger rate. Some additional margin on the link (of order a factor of 2) will be obtained by data compression, and careful buffering of the events will ensure capture of event clusters. The local data recording will also be capable of capturing event clusters which exceed the telemetry capacity; in these cases an event selection will be done locally in software and a subset of the events will be sent to telemetry while the remainder will be archived on board.

TDRSS telemetry can be maintained on a
near continuous basis. We anticipate using this option for ANITA to support the highest possible trigger rate. In Table 6 we summarize features of the telemetry downlink. All transmitted data is archived on the Standard Instrumentation Package (SIP) which is procured from the NSBF. In addition, we will provide redundant onboard storage for all transmitted data as well as additional archived engineering and excess event cluster data. The event cluster storage in particular will exceed the telemetry capacity by a factor of 10 overall.

Table 6: Downlink information

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
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<tr>
<td>Data volume</td>
<td>43 Mbytes/day</td>
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<tr>
<td>Bit error rate</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td>Onboard storage</td>
<td>$\geq 40$ Gbyte</td>
</tr>
<tr>
<td>Power available</td>
<td>In NSBF SIP</td>
</tr>
<tr>
<td>for communications</td>
<td></td>
</tr>
<tr>
<td>Data dumps per day</td>
<td>near-continuous</td>
</tr>
<tr>
<td></td>
<td>TDRSS telemetry</td>
</tr>
<tr>
<td>Data destination</td>
<td>NSBF data center, Palestine, TX</td>
</tr>
<tr>
<td>Science Data</td>
<td>UCLA Mission</td>
</tr>
<tr>
<td>destination</td>
<td>operations center</td>
</tr>
</tbody>
</table>

Command uplinking has several aspects which require some explanation. During the initial portions of the flight, a line-of-sight link is established with the ground control center at McMurdo station, with relatively high bandwidth. This bi-directional link allows for rapid transfer of engineering and health data which is critical to an early assessment of the mission status and health. In our case, we will plan to exercise this link to provide dense samples of antenna cluster information to establish that the receiving system is functioning correctly and that the antenna time series appear normal. The du-
ration of this period should be of order 1 day. Clearly this effort requires a skilled team on site in Antarctica which is distinct from the science team which will be receiving the data at the U.S. mission operations center.

Once the mission has passed this period, the uplinking will be through TDRSS telemetry at much lower rates. We do not anticipate any reprogramming necessary during this phase of the mission, but the architecture will provide the possibility of restructured software triggering if it is deemed necessary by risks posed from potential RF interference. We discuss these possibilities in the following section.

2.3 Background Interference. Because ANITA will operate with extremely high radio bandwidth over frequencies that are not reserved for scientific use, the problem of radio backgrounds, both anthropogenic and natural, is crucial to resolve. We have noted above that the thermal noise floor provides the ultimate background limitation, in much the same way that photon noise provides the ultimate limit to optical imaging systems. Here we briefly address backgrounds from other sources, some of which are treated in more detail in a later section.

2.3.0.1 Lightning & Cosmic Ray Air Shower backgrounds. Lightning is known to produce intense bursts of electromagnetic energy, but these have a spectrum that falls steeply with frequency, with very little power extending into the UHF and microwave regimes. Lightning is also unknown on the Antarctic continent, although it does occur over the Southern Ocean [66, 67]. We do not expect lightning to comprise a significant background to ANITA.

Cosmic ray air showers at energies above 0.1 EeV also produce an electromagnetic pulse, known from observations since the late 1960’s. Although these pulses may have a weak component associated with the Askaryan effect, the dominant emission comes from synchrotron radiation in the geomagnetic field. Again this radiation falls steeply at frequencies above 100 MHz, and although such events may occasionally trigger a system like ANITA, the spectral characteristics will be unmistakably different from the ice cascade emission, the arrival direction (from above the horizon) will give further rejection of this unlikely background.

2.3.0.2 Snow Electrification. Snow electrification and apparent bulk discharges associated with this process have been reported anecdotally in Antarctica for snow during intense storm events [69] and wind-driven surface snow [70]. In the former case, the background electromagnetic noise levels were noted to rise a factor of 100 during some events, over the 3-30 MHz (HF) radio band. The level of possible interference over the VHF and UHF bands is at present unknown for either case, although wind-driven snow EMI was found to be negligible in one set of experiments [70]. Since storms are generally rare and often confined to coastal areas during the Antarctic flight season, we do not anticipate a major problem from this source, but we intend to continue to monitor this as a potential risk during the coming Antarctic seasons, during which we expect to have ANITA personnel at McMurdo or the South Pole every year.

2.3.1 Anthropogenic Backgrounds. Backgrounds from man-made sources do not in general pose a risk of being mistaken for the signals of scientific interest, because there are no known anthropogenic sources (other than calibration sources specifically designed for our experiment) which can emulate the expected signals. However, man-made sources can pose a risk of interfering with the operation of the instrument. We discuss such issues in more detail in the mission implementation section below.

Interference from man-made terrestrial or orbital sources is a ubiquitous problem in all of radio astronomy. In this respect ANITA will have to face a variety of potential interfering signals with various possible impacts on the data acquisition and analysis.
2.3.1.1 Satellite signals. Fortunately for ANITA, satellite transmit power is generally low in the bands of interest. For example, the GPS constellation satellites at an altitude of 21000 km, have transmit powers of order 50W in the 1227 MHz and 1575 MHz bands, with antenna gains of 11-13 dBi. The implied power at the earth’s surface is -160 dBW m\(^{-2}\) maximum in the 1227 MHz band. The implied field strengths for ANITA are of order 0.2 \(\mu V \text{ m}^{-1}\). These levels are easily filtered with tunable notch filters for the satellite frequencies of interest.

All earth-orbiting satellites are constrained by the International Telecommunications Union (ITU) to maintain a power level that produces no more than -154 dBW/m\(^2\) at earth. These power levels are weak enough that they will not saturate ANITA LNAs even if they are not pre-filtered. Since they are narrow-band signals they cannot produce the broadband EMP events that ANITA will be sensitive to. However, an important aspect of the ANITA front end will be a filterbank that removes these and other known narrow-band signals prior to launch. This will reduce the effective system temperature which would otherwise be increased somewhat by the integrated effects of narrow-band carrier signals diluted across the ANITA bandwidth.

2.3.1.2 Terrestrial signals. The primary risk for terrestrial signals is not that they trigger the system, since they will almost certainly do so on occasion. Such triggers are easily recognized in post analysis since they cannot reproduce the characteristics of the cascade pulses. The greater issue for ANITA occurs if there is a strong transmitter in the field of view which saturates the LNA, causing its gain to droop so that the sensitivity in that antenna is lost. Our present LNA design will tolerate up to about 10 dBm output before saturation, with in input stage gain of order 25 dB. Thus a signal of 10\(\mu\)W coupled into the antenna would pose a risk of saturation and temporary loss of sensitivity.

Since the antenna effective area approaches 1 m\(^2\) at the low end of the band, ANITA could therefore tolerate up to a 1 MW transmitter at or near the horizon, or a 5 kW transmitter near the nadir. Most of the higher power radar and other transmitters in use in Antarctic are primarily at the South Pole and McMurdo stations. The South Pole station is not in ANITA’s view during a typical flight, and McMurdo station will only be in view during brief periods during the flight.

2.3.2 EMI Background Survey. As part of the 2002 Space Research and Technology NASA-OSS grant under which ANITA research and development is ongoing, a piggyback payload has been accepted by NSBF and scheduled for an Antarctic flight in the 2002-2003 Antarctic season. The flight payload has been designated Anita-lite, and will fly as an integrated system aboard the Trans-Iron Galactic Recorder (TIGER) payload. Anita-lite will fly a pair of ANITA prototype antennas, a prototype trigger system, and commercial digitizers to sample the impulsive background noise from the balloon altitudes. Significant effort will be required to reduce interference from the host payload, but once this is done, Anita-lite will provide important data for reducing the risk to the primary ANITA instrument.

To complement the Anita-lite measurements, we have (as noted in a previous section) already performed ground-based Antarctic measurements of impulsive and thermal ambient backgrounds from the South Pole Station, and the results have to date been encouraging, indicating that backgrounds in Antarctica appear to be extremely low, probably among the lowest on earth. We will continue to perform additional ground-based tests over the next several years as experiments of opportunity, since part of the ANITA team (Barwick, Besson, Cowen) are scheduled to be in Antarctica for other projects.

2.3.3 Mitigation strategies for interference. We conclude this section by describing sev-
eral strategies we plan to employ for mitigation of RF interference problems. As we have noted, these will be adapted as our knowledge base of the actual RF environment in Antarctic increases, and will be finalized following the background survey described above. We note that these techniques are in many cases highly developed, either due to our experience with the analogous GLUE experiment, or in developing other low-noise radio astronomical instrumentation.

The most effective mitigation strategy in our system will be the requirement for extremely broad-band coincidence of a trigger event across multiple antennas, multiple frequency bands, and dual polarizations. These requirements effectively force any interfering signal that can trigger to appear very similar to the signal of interest, a subnanosecond, highly-polarized pulse. Such pulses are quite difficult to produce in pure form in practice. Although there are high-frequency radar systems that employ such pulses, these are primarily used in microwave systems above 5 GHz. High-power switching transients can produce pulses but they are never completely isolated or band-limited, and tend to produce spectra that fall off at higher frequencies.

Another source of potential interference triggers for ANITA will occur when a narrow or moderately broadband persistent signal appears within one or more of the trigger sub-bands and the additional power effectively raises the thermal noise of the band to a higher level. Our response to this is to enforce a so-called noise-riding threshold similar to that of FORTE for our digital comparators. This will allow that particular channel to ride up with the increasing noise level and thus not increase its rate of threshold crossing events. The threshold level will be recorded at a slower rate to ensure that the sensitivity and energy threshold of the instrument can be established as a function of time in post-analysis.

2.4 Status of ANITA under PI funding and ROSS SR&T Grant. As noted in an earlier section, ANITA is currently well beyond a conceptual phase, having been selected for an Antarctic LDB flight under the Research Opportunities in Space Science (ROSS) 2002 Particle Astrophysics Space Research & Technology Program, which began in NASA Fiscal year 2003 (October 2002). In addition, several aspects of ANITA have been under study and development since mid-2001, funded out of the PI’s startup support at the University of Hawaii. Before discussing the plans for ANITA development under the Explorer program, we present a summary of the current state of development.

Efforts to develop ANITA to date have focused on better understanding of the 1) Askaryan pulse process; 2) optimal antennas for its detection; 3) low-power digitizers for very high bandwidth, transient signals; 4) characterizing the Antarctic environment and ice transmissivity for radio waves; 5) investigating the high frequency electromagnetic properties of graphite composite structures for the gondola; and 6) development of ground-truthing calibration signals for determining instrument sensitivity during the flight. Much of the efforts recently have been driven by the selection of the ANITA-lite EMI background survey payload for a piggyback flight aboard the host TIGER payload for this year’s LDB season in Antarctica.

With respect to 1), the PI and Prof. Saltzberg completed a second, more detailed measurement of the Askaryan radiation at SLAC in the summer of 2002, as noted in an earlier section. Antenna studies continue and will be accelerated in the near future as a new 90 m$^3$ anechoic chamber, funded out of the PI’s startup support, comes on line by early summer of this year. The digitizer development is detailed below, and initial Antarctic EMI studies were described above (the SPIN experiment). Initial evaluation of intercalated graphite as a gondola material looks quite promising, and we have established initial contact with NASA researchers regarding adap-
2 MISSION IMPLEMENTATION

tation of this material for structural applications. Finally, preparations for a ground-truthing system for ANITA-lite have brought us well up the learning curve for what will be required to successfully develop and deploy a pulser system at either McMurdo or an outlying station such as Vostok, and plans for such a deployment for this year are moving steadily ahead.

It is fair to say that, although the ROSS award will only have been fully active for 6-8 months prior to the possible Explorer selection, ANITA will have benefited from well over a 18 months worth of steady development and study work, as well as considerable prototyping of hardware. The advantage of this to the current proposal is that it significantly reduces both schedule and cost risk. Conversely, the advantage of moving from the ROSS to the Explorer program is clear: a much-enhanced science return at much-reduced mission risk.

2.5 Development, Integration, & testing. ANITA may be grouped into several well-defined subelements that can be separately developed at different institutions and then later integrated. For purposes of tracking the mission development, we define these subelements primarily by their hardware divisions. Fig. 11 provides a schematic description of the planned flow of integration for ANITA.

2.5.1 RF payload. The RF payload consists of the antennas, the RF conditioning system (consisting of low-noise amplifiers, filters, and secondary amplifiers), and the digitizers. This system will be developed at both JPL and UH, taking advantage of the lower university labor costs. The system will be integrated at JPL prior to delivery to the ballooncraft at UCI, including some environmental testing for subcomponents if necessary. The balloon environment and launch requirements do not mandate space-qualified parts, nor are there any extreme vibration or shock conditions to be survived, so in general off-the-shelf equipment and standard electronic circuit development techniques can be used, with care for thermal and low-pressure considerations. For cases where the latter issues need to be addressed for a given part or component we anticipate a modest environmental test program as part of the RF payload development.

2.5.2 Control & data acquisition system. The onboard computer will be a standard PCI-bus based system flown already on other balloon missions. We do not anticipate any unusual requirements to be levied on this computer during the flight. We plan a pair of redundant systems on board with the capability to software swap to the second processor if necessary, via ground communication through the SIP. These will be developed under the direction of Prof. Beatty at Penn State, with help from Bartol and UM.

2.5.3 Instrument integration. The instrument integration of RF payload and control/data acquisition will be completed at JPL. Because much of the structural backbone of the complete system resides with the gondola, which will not be available during this phase, the antennas and electronics will be designed in modules with interface requirements that allow them to be tested separately before they are later brought to higher level integration with the gondola.

2.5.4 Gondola. The gondola systems, consisting of the strongback frame of the ballooncraft, the power system, solar panels, wiring, and other miscellaneous ancillary components, will be developed and integrated through UC Irvine with engineering support from both JPL and UH. UCI may subcontract a portion of these subelements to other university partners, but the complete integration will take place in a UCI high bay.

There are several subelements of the gondola system which are likely candidates for subcontract work or procurement from other institutions; among these are the NSBF SIP, the antirotation and onboard navigation system. The solar panels are likely to be procured from the same vendor who developed the high efficiency panels for the Deep Space One project. If
2 MISSION IMPLEMENTATION

more conventional panels are shown to meet the power needs of the project, they can be procured through the NSBF.

2.5.5 Gondola/instrument integration. The integration of the gondola and the instrument will take place at UC Irvine. This phase of the development program will involve both mechanical, electrical, and computer integration as the antenna modules and instrument electronics and computers are installed, and the telemetry interface to the computer is made. An alternative here would be to move the gondola package to JPL and perform the integration there. Prof. Barwick has an agreement in place with UCI Administration for the use of the high bay during this period of instrument integration.

2.5.6 Antenna calibration. Final antenna calibration will take place at the JPL mesa antenna range, which has complete capabilities for both anechoic chamber and free space calibration from VHF through microwave frequencies. Some early antenna calibration at the modular level will have taken place and thus the final calibration will be designed to address the major issues of the complete antenna array. We anticipate that the individual antenna beam patterns will be modified by the cluster array configuration. Thus we plan to calibrate the entire integrated package with all gondola components in place, so that the final beam pattern of the complete system will be known over the entire frequency band of interest, from 0.2 up to 1.2 GHz. During this calibration sequence we will also make measurements of the emissions from the instrument in an anechoic chamber, with the potential at this point of performing additional electromagnetic shielding to mitigate self-interference problems.

2.5.7 Environmental test & Engineering test flight. Once the antenna calibration is complete we plan to perform a complete environmental test of the instrument only, using one of the larger JPL chambers, with capability for complete low-pressure and solar illuminance

Figure 11: Flow diagram of the development, integration and testing plan for ANITA.
testing. This test will primarily be a confirmation test, since individual parts will have undergone such tests prior to final integration.

A test flight in Ft. Sumner, New Mexico, is planned for September 2005 as a check out of the entire package. The flight will retire risks associated with the basic functions of the system, such as computer or electronics failure, failure of the ballooncraft subsystems, etc. However, it will provide only basic functional data on instrument performance since the RF interference environment will be much worse than that at the South Pole. Anthropogenic RF noise over the continental US is on average up to 1000 times higher that in quiet regions of the earth such as in Antarctica, and it will be difficult to find any portion of the flight path from Ft. Sumner where the balloon would not be in direct view of a multi-kW transmitter of some kind. To reduce hardware risk only a portion of antennas and the photovoltaic array may be flown during the engineering flight.

2.5.8 Flight delivery. Following this final test and a period of potential refurbishing or necessary modifications, we ship the complete system to Palestine where it undergoes final preparation for shipping to McMurdo for the following December.

2.5.9 Ground systems & calibration. Parallel to these other efforts are the development of a ground data system, including the science data center at UCLA, and a deployed external calibration system, developed at UCLA and UH. The ground data system makes use of standard approaches and equipment procured from or provided by the NSBF, and will require some interface definition and compliance testing for these interfaces, primarily for managing the telemetry.

The calibration system will be required to provide the instrument with a recognizable and unique signal designed to allow in-flight calibration of the antenna response. At least one system will be deployed near McMurdo for viewing during the line-of-sight period of the flight. If it is deemed necessary, additional self-contained systems will be deployed along the probable flight path to enable further calibration sequences during the mission.

2.6 Resource budgets.

2.6.1 Mass. Engineering estimates of the mass requirements are shown as an allocation, based on the preliminary instrument and gondola model, in Table 8. The current best estimates (CBE) are based on minimal efforts at lightweighting the gondola frame or electronics systems, and we anticipate that we will gain back some margin as the design proceeds and addresses some specific lightweighting opportunities.

2.6.2 Power. ANITA power requirements (Table 9) are relatively high for a balloon mission because of the large number of channels that must be amplified and digitized. We propose to use a solar array of high efficiency (triple-junction) cells in conjunction with a 2x concentrator. The concentrator is not required but reduces the cost by reducing the total number of cells required. The concentrator has a relatively flat response in one dimension out to ±10° and then drops rapidly. This axis would be along the direction that is stabilized. The solar array would have a cosine response in the other dimension. The variations in the solar height during a flight will introduce variations in the power by less than 2%. Our baseline PV array is rated for 1.4kW, but we expect a derating of ~10% due to thermal inefficiency. Our present power allocation is therefore 1275W.

The battery system is intended to fulfill several functions. The batteries will provide power from the time ground power is disconnected until the solar panels are operational. The batteries will also provide power for the attitude control system to enable return to Sun point for the solar panel and they will allow some data to be taken if the solar panels fail. The battery system is currently planned as a bank of Li/Thionyl Chlo-
Table 8: ANITA Mass budget.

<table>
<thead>
<tr>
<th>System/Subsystem/item</th>
<th>CBE (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science Payload (incl. reserve)</strong></td>
<td>1554</td>
</tr>
<tr>
<td>Gondola (subtotal)</td>
<td>667</td>
</tr>
<tr>
<td>Ring antenna mounts</td>
<td>48</td>
</tr>
<tr>
<td>Nadir antenna mount</td>
<td>11</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>17</td>
</tr>
<tr>
<td>Batteries</td>
<td>58</td>
</tr>
<tr>
<td>crush pads</td>
<td>6</td>
</tr>
<tr>
<td>Structure/strongback</td>
<td>527</td>
</tr>
<tr>
<td><strong>Instrument (subtotal)</strong></td>
<td>528</td>
</tr>
<tr>
<td>Antennas</td>
<td>367</td>
</tr>
<tr>
<td>Digital electronics</td>
<td>56</td>
</tr>
<tr>
<td>RF electronics</td>
<td>101</td>
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<tr>
<td>Power conditioning</td>
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</tr>
<tr>
<td><strong>Payload Reserves (30%)</strong></td>
<td>359</td>
</tr>
<tr>
<td><strong>Ballooncraft</strong></td>
<td>469</td>
</tr>
<tr>
<td>SIP &amp; therm. shield</td>
<td>172</td>
</tr>
<tr>
<td>LDB Batteries</td>
<td>27</td>
</tr>
<tr>
<td>Ballast system</td>
<td>101</td>
</tr>
<tr>
<td>LDB photovoltaics</td>
<td>59</td>
</tr>
<tr>
<td>LDB antenna system</td>
<td>18</td>
</tr>
<tr>
<td>Rotator</td>
<td>91</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>2023 kg</td>
</tr>
</tbody>
</table>

Ride primary batteries with 29 kw-hrs of capacity. This is sufficient power to run the instrument for 24 hours.

A second solar array and a second set of batteries are flown on the gondola as part of the SIP. This hardware powers the balloon control system, and the telemetry system. The designs for this hardware exist and have been flown many times. This solar array and power system for the SIP will be provided as part of the support costs paid to the NSBF.

In Table 10 we show the summary of the mass and power budget values, including 30% power reserves, and mass reserves on the science instrument and gondola. No reserves are held on the NSBF supplied equipment (balloon-craft in the table) since these are measured values. The present margins on the totals are also shown.

2.7 Attitude control & knowledge.
We do not anticipate any stringent control or knowledge requirements on the balloon attitude and pointing during the mission. We have specifically designed ANITA to be insensitive to orientation to first order, since the antennas themselves have a wide angular response. Since the highest precision we can attain at present in angular knowledge is of order \(2 - 3^\circ\), we require a knowledge of order 1\(^\circ\) tilt angle with respect to the local gravity vector. This allocation thus adds no more than 10% uncertainty to our overall elevation angle determinations. Since balloon gondolas do experience pendulations, we will require an update in this knowledge at a rate of order 10 times the highest pendulum frequency to avoid any possibility of aliasing the tilt measurement. We anticipate an update rate of order several Hz will be required.

Control of the tilt direction is not necessary as long as the tilt amplitude does not exceed 10\(^\circ\), and we do not anticipate tilt amplitudes of this magnitude. Control of the azimuth is also not required at any level more stringent that 10\(^\circ\), and this should be easily accommodated by a standard sun-pointing anti-rotation device.
2.8 Mission Technology. ANITA represents a novel approach to neutrino astronomy which is itself a relative newcomer to the astrophysics discipline. However, the technology employed by ANITA is largely mature and we do not anticipate any significant technology development issues. In this section we describe the required technology, its heritage and maturity level.

2.8.1 Heritage & maturity of mission elements. The primary heritage of the ANITA design is based on the functional elements employed in the GLUE project, which has established the basic approach to be used for rejection of background and specific triggering on and sampling of the pulse waveforms. Given that these functional elements are now reasonably well understood, the heritage and maturity of the subelements of the instrument can be described with some confidence.

Antennas. ANITA makes use of standard moderate-gain antenna elements as the primary front-end sensors, as described in previous sections. The antenna modules have a high level of technology readiness and the design is mature at this stage. Prototypes will also be flown as part of the ANITA-lite EMI survey flight this year.

RF conditioning. The antenna signals require front-end amplifiers with a gain of order 50 dB, and a noise temperature of less than 80 K. Such amplifiers are commercially available at a high technology readiness level, and the costs are relatively low. Several suitable amplifiers have been already procured as part of the preparation for the ANITA-lite EMI survey flight.

Digitizer. The custom digitizer development represents one of the important new technology areas of ANITA. Digitizers of comparable bandwidth exist in commercially available parts, but the power requirements are typically at least several watts per channel or more, which becomes a serious issue for the power budget of ANITA which is already stretched. In addition, use of these commercial parts would require a very high throughput digital signal processor to

<table>
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<th>Parameter</th>
<th>value</th>
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<td>Control method</td>
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</tr>
<tr>
<td>Control reference</td>
<td>solar</td>
</tr>
<tr>
<td>Attitude control requirements</td>
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</tr>
<tr>
<td>Ballooncraft attitude knowledge at instrum. interface</td>
<td>±0.33°</td>
</tr>
<tr>
<td>Agility</td>
<td>none</td>
</tr>
<tr>
<td>Deployments</td>
<td>none</td>
</tr>
<tr>
<td>Articulation</td>
<td>none</td>
</tr>
<tr>
<td>On-orbit calibration (antenna response)</td>
<td>Ground-station RF pulser</td>
</tr>
<tr>
<td>Attitude knowledge processing</td>
<td>±0.5° per axis post-processing</td>
</tr>
</tbody>
</table>
manage the digital data stream from many channels at the same time for the purpose of generating the local triggering via software or firmware. For example, four eight-bit digitizers running at 3 Gs/s in parallel on the RF signals from a pair of adjacent antennas will generate a data stream of order 100 Gbit/s, several orders of magnitude above the bus bandwidth of anything presently available at mature technology levels.

To address this problem, Dr. G. Varner of the Univ. of Hawaii Instrument Development Laboratory (IDL) has developed a monolithic 16-channel waveform recorder application-specific integrated circuit (ASIC) with onboard triggering provided by complimentary circuits. A high-level threshold allows triggering based on a large signal in a single channel. In addition, multiplicity logic allows for a coincidence trigger based upon a number of channels exceeding a smaller threshold. A 12-bit on-chip ADC, capable of 2M Conversions/s, provides a digital data stream out. Waveform record length is at least 256 samples per channel with a sampling frequency up to 4GSa/s.

A prototype of the device described here has recently been developed and tested by Dr. G. Varner of the University of Hawaii. Initial results of the device, which uses a CMOS 0.25µm process, have demonstrated sampling rates well above 3Gs/s, and spectral frequency response beyond 1 GHz, with a power consumption of only 275 mW per device. A second generation device which will extend to the full ANITA bandwidth is now in final design and simulation stages, and will be on hand by late summer of this year, prior to the start of the Phase A study for ANITA.

As readout can take up to 10ms, deadtime is avoided by the use of multiple chips in parallel, thus providing multi-hit capability. Taking advantage of the low-power and compact size of these chips, in addition to multi-buffering, interleaved sampling at higher effective sampling frequencies or simultaneous logging of multiple frequency bands may be accomplished.

The flexibility afforded by the new design enables the possibility of performing the digitization on only those signals which occur in multiple antennas, polarizations, and frequency bands simultaneously. Once a trigger is found, the 256 sample signal storage array, which forms a continuous analog ring buffer, is latched and read out with an analog-to-digital converter. This triggered-digitizer approach presents an enormous improvement in throughput requirements for the system.

**Global Trigger Logic.** We intend to implement the global trigger logic in Xilinx field-programmable gate arrays. The technology readiness for this application is high and the logic requirements for the FPGAs are relatively straightforward.

The closest analog in radio-frequency systems to ANITA’s trigger is probably found in low-SNR radar applications, where single-pulse recognition is necessary. In ANITA’s case, the trigger system makes use of may different channels that simultaneously detect the leading edge of any RF impulse that arrives at the instrument. For example, in the sequence of pulses shown in the simulation of Fig. 2 above, the trigger system would actually have 72 different potential channels in which the impulse could be detected: two polarizations for each of the 9 antenna signals shown, with four 250 MHz trigger bands for each polarization.

The trigger would form in a hierarchical manner, with the 8 channels from a single antenna forming the lowest level of the hierarchy. If a pre-set fraction of these channels exceed a certain amplitude threshold, a logic gate is enabled at the next highest level of the hierarchy, the adjacent antenna pairs. If any of several user-set antenna-pair patterns then exceed threshold and also enable their logic signals, a global trigger is formed, all of the antennas are digitized, and the event is recorded as a telemetry candidate. This triggering scheme is indicated schematically in Fig. 12. Here we have shown the 8 channels for a single antenna,
with simulated pulses from the same simulation used in Fig. 2. The multiplicity logic can be thought of as a simple (positive as shown here) sum of logic levels of the channel discriminators here, indicated by a negative-going pulse beneath each of the radio signals. At each higher level of the hierarchy, the trigger pulse generated by the lower level becomes part of the logic sum for the next level until the global trigger condition is met.

Further onboard analysis then would characterize the event’s telemetry priority according to its neutrino candidate likelihood. Similar array trigger logic methods have been in use for many years in high energy physics experiments, and the ANITA team has several members, including Gorham, Barwick, Beatty, Saltzberg, and Varner, with extensive experience in these methods.

3 ANITA MANAGEMENT AND SCHEDULE

3.1 Management approach The Principal Investigator, Prof. P. Gorham, is responsible for the success and scientific integrity of the ANITA Project and is the final project authority on all issues. To execute that responsibility, the PI has established the ANITA Project as an integrated partnership; each member brings unique strengths to the project team that will enable it to complete the project on schedule and on cost, without compromising the project’s science objectives. The PI provides his proven ability in science team leadership and science data processing, modeling and analysis. JPL provides its expertise in project management, system engineering, and mission operations. JPL also provides expertise in RF instrument development and calibration (including background measurement). Investigators specializing in theory, modeling, and data analysis have been recruited as team members. Because of the complexity of balloon operations in Antarctica, particular care has been paid to the inclusion of investigators (six team members representing three different institutions) with balloon experience. The members of the ANITA Project team are committed to full and open communications among all elements of the project in a manner similar to that practiced among Discovery-class missions under current development at JPL.

3.1.1 Management organization. The ANITA Project management organization is shown in Figure 13. The PI is the central person responsible to NASA Headquarters for successful execution of the mission. He is prepared to recommend termination of the project in the unlikely event that achievement
of the performance floor should become im-
possible with the committed project resources.
The PI is supported by the ANITA Advisory
Board, which includes the PI as chairman. The
members of the advisory board are from the
institutions participating in the ANITA Project.
The primary role of the advisory board is to
assure that these institutions provide the PI with
the support that the project needs from their
respective organizations.

3.1.2 Decision-making process. The PI ap-
points the JPL Project Manager, with the con-
currence of appropriate JPL line and program
management, and assigns project management
responsibility to him. The Science Team is un-
der the leadership of the PI, but all financial re-
porting is through the Project Manager. All sys-
tem managers report to the PM. Decision mak-
ing will occur at the lowest level possible while
ensuring that decisions made in one system do
not adversely affect other system areas or impact
the prospects for successful science data return.
The PI is the final project authority for all deci-
sions that cannot be resolved at lower levels and
in particular for any involving the science data
deliverables.

3.1.3 Teaming arrangements. A summary
of the participating institutions and their primary
roles as part of the ANITA team is summarized
below in Table 12. At present, no formal agree-
ments for teaming arrangements with vendors
have been made; these may or may not be ap-
propriate for the scale of a long duration balloon
mission.

Specific roles and responsibilities of the
Principal Investigator and the Project Man-
ger. The Principal Investigator is in charge
of the investigation and maintains full author-
ity for its scientific integrity and for the in-
tegrity of all other aspects of the mission, in-
cluding Education and Public Outreach. He
delegates the responsibility for implementation
of the flight system to the JPL Project Man-
ger. The Project Manager will plan, coordi-
nate, and monitor system design and implementa-
tion during all phases of the project. The
Project Manager is also responsible for over-all
risk management. Upon selection by NASA,
a Project Plan will be developed that will in-
clude specific spending plans and development
milestones that will be used as the basis of an
earned value performance measurement track-
ing system. The Project Plan will also docu-
ment the initial level of project reserves and a
schedule for their depletion tied to key project
milestones. The PI will have approval authority
over the Project Plan and all other project level
documents, as well as any changes to those doc-
uments. The PI will report to NASA all changes
to the plan and descope options exercised, for
NASA concurrence. The Project Manager will
report monthly against the Project Plan and pe-
riodically review the completion plan to assure
that it is proceeding within schedule and cost.
The Project Manager will report progress and
any problems to the PI in weekly meetings or
teleconferences. Monthly reports to the appro-
priate NASA Program Office will be prepared
by the Project Manager and approved by the PI.

3.1.4 Risk Management. The mission ar-
chitecture has been designed to minimize risk;
in particular the choice of development of two
identical payloads is a choice specifically made
to minimize risk to the overall mission success.
The top six highest risk items are listed in Ta-
ble 13, along with mitigation strategies that are
costed and planned as part of the baseline mis-
sion architecture. Upon selection, a detailed
risk management plan will be developed that
will provide a systematic approach to assess-
ment and mitigation of all significant risks. JPL
has recently developed a list of principles for
design, validation, and operations of missions
that will guide risk management of the ANITA
Project. The JPL Design Principles incorporate
the many lessons learned on management of risk
of deep space missions. The key element in
managing project risk is the establishment and
management of appropriate project reserves, including both cost and schedule reserves. The 30% reserves in this proposal are in accordance with the JPL Design Principles. An important element in risk management is the establishment of an integrated baseline of requirements, schedule and cost, against which progress will be tracked in order to determine as early as possible when project reserves will be needed. The basis of estimate for the cost reserves for ANITA is described below, and the basis of estimate for schedule reserves is addressed in section 3.2 which follows.

A key element in our risk assessment and management approach is the use of informal peer reviews at the sub-system level for all JPL and partner-provided project deliverables. A project risk team review will be held within 12 months of launch to assess launch readiness. The current proposal includes an estimate of the cost associated with risk management based on the analogy with similar missions currently under development at JPL.

3.2 Project Schedule. A project schedule showing all mission phases and major milestones is shown in Figure 14. We note that ANITA is unique in already having support for first LDB-flight development through the SR&T program, and we have developed an integrated schedule which reflects this. We anticipate a relatively seamless transition if selected, such that personnel involved in engineering development and prototyping for the SR&T program would see minimal impact from the Phase A study, which would be managed at the co-investigator levels. This allows for a transition to the Explorer program which maximizes the utility of the prior design and development that are afforded by the SR&T program.

The project critical path is represented by the RF instrument subsystem instrument and later by the full instrument, leading to test flight integration. There are 30 days of fully funded schedule reserve on the critical path just before delivery to payload integration. There is another 60 days of funded schedule reserve follow-
### ANITA MANAGEMENT AND SCHEDULE

#### Project Phases:
- SR&T development
- Phase A/B
- Phase C/D
- Phase E

#### Project Milestones:
- Prelim. Design Review
- Critical Design Review
- Engineering test flight
- Project Initiation Conf. (PIC)
- Mission Readiness Review
- Launch #1
- Launch #2
- Launch #3

#### Project Tasks:
- Requirements definition
- Design development
- Prototype develop/test
- EMI survey develop.
- EMI background survey
- RF Instrument development
- Onboard DAQ system
- Flight software development
- Gondola development
- Test flight integration
- Calibration & testing
- Test flight launch/recover
- Final Payload Integration
- Calibration & testing
- Payload to NSBF
- Ground data systems
- Data analysis SW devel.
- Launch & Recover
- Refurbish payload
- Data Analysis
- Reporting/Publication

<table>
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<tr>
<th>Mission Element</th>
<th>Fiscal year</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<td>Quarter</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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</table>

Figure 14: ANITA project schedule.
### Table 12: ANITA Participating Team members & Expertise

<table>
<thead>
<tr>
<th>Team Member</th>
<th>Responsibility/Capability</th>
<th>Relevant Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal Investigator</td>
<td>Science Team leadership &lt;br&gt; Integrity of science investigation &lt;br&gt; RF expertise</td>
<td>PI for GLUE, ANITA SR&amp;T projects &lt;br&gt; Radio detection of high energy particles &lt;br&gt; Neutrino astrophysics</td>
</tr>
<tr>
<td>University of Hawaii</td>
<td>Science management &lt;br&gt; Antenna development &lt;br&gt; Science data analysis &lt;br&gt; Instrument modeling &lt;br&gt; Digitizer development</td>
<td>Neutrino astrophysics &lt;br&gt; Cosmic ray astrophysics &lt;br&gt; RF instrument development &lt;br&gt; Various neutrino experiments &lt;br&gt; Prototype digitizer completion</td>
</tr>
<tr>
<td>Jet Propulsion Laboratory</td>
<td>Project Management &lt;br&gt; System engineering &lt;br&gt; Mission operations &lt;br&gt; RF instrument &lt;br&gt; Mission assurance &lt;br&gt; Payload I&amp;T</td>
<td>Management of numerous major NASA missions; development &amp; deployment of complex space- and ground-based instruments; history of high success-rate missions</td>
</tr>
<tr>
<td>University of California, Irvine</td>
<td>Gondola development &lt;br&gt; GSE support software &lt;br&gt; Science data analysis &lt;br&gt; Payload integration</td>
<td>Balloon and payload development &lt;br&gt; HEAT &amp; other balloon experience &lt;br&gt; Neutrino astrophysics &lt;br&gt; Neutrino data modeling &amp; analysis &lt;br&gt; AMANDA neutrino observatory</td>
</tr>
<tr>
<td>University of California, Los Angeles</td>
<td>Antenna calibration &lt;br&gt; Ground data system &lt;br&gt; Science data analysis</td>
<td>RF instrument development &amp; calibration &lt;br&gt; Neutrino astrophysics &lt;br&gt; Large data set management</td>
</tr>
<tr>
<td>Pennsylvania State University</td>
<td>Balloon operations &lt;br&gt; Trigger design support &lt;br&gt; Balloon avionics &lt;br&gt; Flight Software</td>
<td>CREAM ULDB balloon payload &lt;br&gt; IceCube Project leadership &lt;br&gt; Cosmic ray &amp; neutrino astrophysics &lt;br&gt; Auger cosmic ray observatory</td>
</tr>
<tr>
<td>Bartol Research Institute, University of Delaware</td>
<td>Balloon operations &lt;br&gt; EMI background survey &lt;br&gt; Science data analysis &lt;br&gt; Archiving &amp; modeling</td>
<td>Balloon and payload development &lt;br&gt; Cosmic ray &amp; neutrino astrophysics &lt;br&gt; Modeling &amp; analysis &lt;br&gt; RF instrument calibration</td>
</tr>
<tr>
<td>University of Minnesota</td>
<td>Balloon navigation &lt;br&gt; Onboard data storage &lt;br&gt; Balloon avionics &lt;br&gt; Science data analysis</td>
<td>Balloon and Payload development &lt;br&gt; Cosmic ray astrophysics &lt;br&gt; RF instrument development &lt;br&gt; CREAM ULDB payload</td>
</tr>
<tr>
<td>University of Kansas</td>
<td>On-ice calibration &lt;br&gt; Antenna development &lt;br&gt; Science data analysis &lt;br&gt; Instrument modeling</td>
<td>RICE/AMANDA experiment &lt;br&gt; Antarctic science experience &lt;br&gt; RF instrument development</td>
</tr>
</tbody>
</table>

We complete this section with a more de-

...
Table 13: ANITA Risk Mitigation Strategies.

<table>
<thead>
<tr>
<th>Risk Element</th>
<th>Mitigation Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthropogenic RF background produces saturation of LNAs</td>
<td>SR&amp;T EMI background survey planned to establish probable levels of interference. LNA protection circuits planned if interference is rare but levels could lead to damage. Hardware filters in place for known bad frequencies. Digital trigger pattern reprogramming capability to be utilized for blanking of individual antennas in high-noise transient conditions.</td>
</tr>
<tr>
<td>Anthropogenic RF background raises system temperature or increases false alarm rate beyond tolerable levels.</td>
<td>Background survey will indicate probability/risk. Digital blanking for individual antennas possible. Noise-riding threshold to be used for reduction of false alarm rate from slowly-varying anthropogenic sources. For impulsive sources, trigger pattern requirements can be adjusted via Xylinx or control software uploads to reject specific threats, since anthropogenic impulses cannot reproduce neutrino signal pulses.</td>
</tr>
<tr>
<td>Gondola is damaged during post-flight landing or recovery.</td>
<td>Budgets for the period following each flight contain resources for refurbishment of the instrument &amp; gondola within the time frame necessary for deployment in the second year following. 2nd payload available for following year.</td>
</tr>
<tr>
<td>Gondola cannot be recovered due to onset of Antarctic winter.</td>
<td>Parts selection &amp; thermal design to minimize damage if system were to winter over. Precipitation is light in Antarctica so risk of snow covering is small. Include transponders which have adequate lifetime for winter-over. 2nd payload deployed for next year.</td>
</tr>
<tr>
<td>Gondola lost over ocean.</td>
<td>Force landing on ice if flight path shows significant risk of straying over open ocean. Second payload ensures mission continuity.</td>
</tr>
<tr>
<td>Failure of telemetry system during flight results in loss of mission data.</td>
<td>Redundant non-volatile on-board storage will record data as backup to TDRSS and SIP telemetry.</td>
</tr>
</tbody>
</table>

Detailed description of aspects of the schedule subelements.

3.2.1 Instrument and Gondola Development, Integration, Calibration, and Testing. We have scheduled a total of 7 quarters for both instrument and avionics development, and 4 quarters for both gondola fabrication and payload integration, calibration, and final testing prior to the engineering test flight. Flight software development continues for a full 12 quarters including reserves, allowing final flight code to be refined through multiple major test milestones. We will proceed directly to engineering-model units of the instrument as soon as the Preliminary Design Review is complete. After CDR is passed we will continue with final flight production.

Because the launch window each year is limited by the length of the Antarctic austral summer, and payloads must be delivered to NSBF Palestine approximately 6 months prior to launch, a slip of the schedule beyond the costed reserves could result in a 1 year delay in the initial launch. Our awareness of the potential costs of such a delay (such as instrument storage, additional labor costs, and additional transportation) are one of the reasons we have adopted a 30% overall project reserves policy,
as noted in the cost section presented below. We note also that such a delay would still satisfy the SMEX AO requirement of first launch prior to August 2008.

3.2.2 Data Analysis, Production, Reporting.
We have provided a total of 8 quarters under data analysis software development. We note here that this includes not only production software for data reduction, but development and refinement of models for the RF pulse production mechanism, for the geographical distribution and depths of ice over the potential flight path, for the mapping of probable ice attenuation lengths, as well as development of detailed models for instrument response and Monte Carlo models for neutrino interactions within the viewed volume. These efforts have traditionally been the domain of university research groups and we have assembled a team with considerable expertise in these areas already.

We have scheduled a six-month period after the conclusion of each balloon flight for data product preparation, followed by an initial release of the flight data to a publicly accessible archive. During the six month period the initial data products would remain proprietary and an early internal release of initial data products would allow investigators the possibility of first rights to publication of the results.

4 ANITA COST AND COST ESTIMATING METHODOLOGY

4.1 Project costs. The total NASA OSS cost for all cost-capped mission phases is estimated to be approximately $31.9M in FY2003 dollars, well within the cost cap of $35M (FY 2003) for Missions of Opportunity. This estimate includes all balloon launch services and ground data support.

Summaries of several more detailed representations of the cost estimate are shown in Tables 14-16. These are broken out by WBS elements (Table 16), by major NASA OSS elements (Table 14) and by mission phase (Table 15). We have adopted a conservative approach toward overall project contingencies at this stage, and have included 30% across-the-board reserves in the NASA OSS costs.

4.2 Methodology.

4.2.1 Project cost estimate. The first step in the cost estimating process was the definition of a detailed, product-based Work Breakdown Structure (WBS), covering all project elements, as described in Table 16. For each element of the WBS, a member of the proposal team was assigned the responsibility for providing a cost estimate. These individual estimates were then combined and rectified to yield a complete WBS-based cost estimate. This estimate is therefore subsystem-based, and is shown in Table 16.

The WBS estimates were then broken out and processed using the JPL Project Cost Analysis Tool, which applies appropriate inflation rates, prorated burdens, and more accurate personnel costs. This tool can also be configured to reflect more closely the requested cost breakdown as described in the SMEX Announcement of Opportunity. This then yields a slightly modified set of budget figures which are used to complete the Tables 14 and 15 below.

The approach used and issues considered in making the cost estimates is summarized in the following subsections for the line items in Table 16.

Project Management, System Engineering, and Mission Assurance. Project Management supports the activities of the Principal Investigator (PI) and the Project Manager. The PI is a university professor and requires support only for his summer salary. The Project Manager is assumed to be a full time JPL Manager I during the development of the instrument and the year of the first balloon campaign, with his/her involvement thereafter being at a decreasing level. Travel costs for both the PI and PM were estimated based on past experience.

Mission Assurance and System Engineering
supports environmental testing of the integrated and calibrated instrument, and support from the JPL 5X organization for mission assurance and safety. The cost of the environmental testing is based on established costs for the use of the environmental test facilities at JPL with a scope determined by the requirements for LDB missions which are not as stringent as spacecraft requirements. Division 5X support for mission assurance and safety is estimated to include one full time engineer prior to the first balloon launch, with the level of support decreasing thereafter.

Science Team Support. This line item supports modeling of the astrophysics and physical processes associated with the science basis for ANITA, algorithm and software development for science data analysis, and science data analysis and interpretation. In addition, we include costs for ongoing efforts to monitor the EMI levels from ground stations in Antarctica, and to get better and more comprehensive measurements of ice properties. The bulk of this work will be done at the institutions of co-investigators, mostly universities. ANITA benefits from a significant heritage of past modeling and analysis work performed by the co-investigators as part of the SR&T program.

RF Instrument Development. The RF Instrument will developed at both the University of Hawaii and JPL, primarily in Division 33. Cost estimates for individual sub-systems (e.g., antennas, RF/IF conditioners, digitizers, flight computer, software and telemetry support) were based largely on experience with prototypes currently under development with the NASA SR&T program, off-the-shelf items, and engineering estimates. Costs for flight-qualification of the parts are included. Flight qualification for LDB flights is not as stringent as for spacecraft, since launch loads and vibration are not an issue, and the radiation environment is not as severe. However, significant attention must be paid to thermal analysis and testing, and vacuum qualification, as well as non-operational shock loads on termination and landing. Thus the digitizer and flight computer categories contain a significant fraction of implicit costs associated with these requirements which will levy the need for testing of individual parts and subassemblies in addition to the integrated testing noted above.

Gondola Development. Gondola development will be led by Prof. Barwick of the University of California, Irvine, with significant engineering support from both Hawaii and JPL. Prof. Barwick has access to and an institutional commitment for use of a high bay facility at UCI for the staging and assembly of the two twin gondolas. We currently plan to use carbon-fiber composite tubing, used extensively in ultra-light structural design, to form the gondola skeleton. Costs for these elements include engineering costs associated with joints and fasteners, as well as some research and development on intercalation materials for optimizing the RF absorbing qualities of the structure so as not to degrade the antenna array performance.

Instrument integration. At the integration stage, we intend to move the primary gondola to a UCI high bay facility, where final integration and testing of the instrument with the gondola will proceed. The second gondola and backup instrument will be delivered to UCI where secondary testing and integration can also proceed in parallel with the primary. This secondary instrument will provide an engineering testbed during the first launch, and then will be readied for flight immediately after the first flight is complete.

Ground Data System Development. During the Antarctic balloon campaigns, data will be transported from the gondola to NSBF Headquarters in Palestine, Texas via a link through the TDRSS satellite. This link and the ground data system, has been developed, tested, and refined by the NSBF. The only costs required of ANITA will be for the establishment of a data base system for the interim storage and transport of data from NSBF to the ANITA archives.

Calibration. The Calibration WBS element
captures several non-flight hardware development tasks, as well as antenna calibration tasks that are specific to determination of the instrument sensitivity. As such they are primarily in the domain of the co-investigator science team, and are costed as such. We have noted above that this element will bring a significant heritage of development under the SR&T program, through the ANITA-lite LDB flight.

**Mission Operations, & Data Analysis (includes archiving).** During balloon campaigns, two persons will be deployed to outlying camps such as Vostok or DOME C in Antarctica to broadcast calibration signals to the balloon-borne instrument. This will permit a monitor of instrument and gondola health. In addition, a team of 2 persons each will be deployed to Palestine, Texas to oversee and monitor the arrival of date from the balloon via TDRSS. This activity does not include the cost of launching and tracking the balloon.

Data analysis costs incurred by the science team are also captured in this item during the post-launch phase E, which includes the additional two LDB launches in successive years.

**Balloon services.** The cost per campaign for the balloon, Helium gas, balloon-gondola integration, launch services, and post-flight recovery is currently given by the NSBF as $1000K for Antarctica. There have been recent increases in cost for other services provided by the NSBF. It will also be necessary to make a one-time purchase ($1000K) of a support instrument package (SIP) from the NSBF. The SIP provides for tracking of the balloon, the recovery of the gondola, and the TDRSS link. Also included in this line item are additional costs for subcontract management at JPL, and additional items such as the sun-pointing rotator ($210K). We do not budget for the purchase of a second SIP for the secondary payload since SIP recovery and re-integration can be accomplished for a single-year turnaround. Loss of the SIP is covered by project reserves.

**Education and Public Outreach.** Following the guidance given in the SMEX AO, Education and Public Outreach will be supported at an ongoing level of 2% per year throughout the lifetime of the project.

**4.2.2 Cost Models.** Cost models for ballooncraft (gondola), instrument, and project costs were used to assess and verify the ANITA project estimates. This included use of the JPL Team X project cost model, which obtained reasonable agreement with the project estimate.

**4.3 Contributed Costs.** There are no direct contributed costs proposed for the current ANITA project.

**4.4 Budget Reserve Strategy.** The ANITA Project has endorsed JPL's standard of a 30% cost reserve on this proposal. This reserve is very conservative for a project with as much heritage and design simplicity as ANITA, but acknowledges the uncertainties that exist in a mission with virtually no science precursor. As such, the proposed reserves address the potential need to increase instrument sensitivity to achieve mission success should the models on which the instrument design is based evolve so as to require it. The ANITA 30% reserve is applied to all project phases and all costs and provides a very high confidence that the ANITA mission will meet project commitments for cost, schedule, and high-quality science return.
## Required NASA OSS Budget Tables & WBS

Table 14: **SMEX AO Required Table B-4:** NASA COST FUNDING PROFILE FOR MISSIONS OF OPPORTUNITY. Fiscal Year costs in Real Year $K; Totals in real year $K and FY03 $K.

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<td>689</td>
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</table>

Table 15: **SMEX AO Required Table B-5:** ANITA Mission Phase Summary for NASA OSS costs. FY costs in real year $K, and totals in real year $K and FY2003 $K.

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Table 16: ANITA Work breakdown structure and associated grass-roots cost estimate.

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<th>2005</th>
<th>2006</th>
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<th>2009</th>
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<th>Totals</th>
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<td>50</td>
<td>10</td>
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<td>7</td>
<td>Calibration</td>
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<td>Antarctic calibration system</td>
<td>120</td>
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<td>Calib. Sys. deployment &amp; services</td>
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<td>8</td>
<td>Balloon Services</td>
<td>500</td>
<td>815</td>
<td>610</td>
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<td>Support Instrument Package</td>
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<td>20</td>
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<td>Campaign Costs (Ft. Sumner/Antarctica)</td>
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<td>265</td>
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<td>560</td>
<td>1120</td>
<td>1120</td>
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<td>9</td>
<td>Operations</td>
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<td>585</td>
<td>345</td>
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<td>200</td>
<td>0</td>
<td>1775</td>
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<td>Ground Data System Development</td>
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<td>10</td>
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<td>9.2</td>
<td>Data Acquisition and Archiving</td>
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<td>100</td>
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<td>65</td>
<td>45</td>
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<td>360</td>
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<td>9.3</td>
<td>Gondola Packaging and Shipment</td>
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<td>120</td>
<td>100</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>380</td>
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<td>Operations Support (Antarctica/Texas)</td>
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<td>240</td>
<td>135</td>
<td>120</td>
<td>100</td>
<td>100</td>
<td>725</td>
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<td></td>
<td>SUBTOTALS</td>
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<td>6947</td>
<td>4190</td>
<td>2650</td>
<td>2935</td>
<td>2585</td>
<td>365</td>
<td>25127</td>
</tr>
<tr>
<td>10</td>
<td>Education and Outreach (2%)</td>
<td>109</td>
<td>139</td>
<td>84</td>
<td>53</td>
<td>59</td>
<td>52</td>
<td>7</td>
<td>503</td>
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<tr>
<td>11</td>
<td>Reserves (30%), except balloon services</td>
<td>1447</td>
<td>1881</td>
<td>1099</td>
<td>628</td>
<td>556</td>
<td>449</td>
<td>112</td>
<td>6172</td>
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<tr>
<td></td>
<td>NASA OSS totals (incl. bridge phase)</td>
<td>7107</td>
<td>8967</td>
<td>5373</td>
<td>3331</td>
<td>3550</td>
<td>3086</td>
<td>484</td>
<td>31898</td>
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<td>2-Month Bridge Phase</td>
<td>96</td>
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</table>
6 ANITA EDUCATION AND PUBLIC OUTREACH

6.1 Relationship to Mission. ANITA uses our imagination and scientific tools to try to see the universe in an entirely new form of ghostly energy: the neutrino. The ANITA EPO Plan will focus on three programs that showcase some of those tools and promote the imagination of inquiry. These programs involve both the Formal and Informal Education community from middle school through university audiences. The following sections detail how we intend to implement this program and Table 17 describes the budget, constituting about 2% of the overall mission total for ANITA. We intend to develop ANITA EPO in close collaboration with a new QuarkNet program currently in its initial phase at UH Manoa. This program, sponsored through Fermi National Accelerator Lab, will provide a framework on which to build ANITA EPO.

Antarctic Balloon Observatory Virtual Explorer (ABOVE): A website for middle school girls using a virtual Three-Dimensional World where visitors receive information about the ANITA neutrino detection mission and use inquiry activities and simulations to experience aspects of ANITA research.

DetectNet. A high school and community college program to develop a teaching array of radio pulse detection systems for high energy cosmic ray particles. One such array in early construction stages (CHICOS) is a collaboration with JPL and managed by Caltech. A startup program (HOPA, Hawaii Observatory for Particle Astrophysics) is currently under study as an extension to the QuarkNet EPO program now under initial development at UH Manoa.

ANITA Academics. A program of engagement with Teacher Education K-12 Relations (TEKR) faculty who work with Pre-service teachers at a Historically Minority Serving Campus of the University of Hawaii Manoa. Partnerships with ANITA scientists will be supported during the duration of the project, providing mentoring by ANITA scientists, and opportunities for internships at a NASA facility to work on Pre-service materials related to ANITA research. At a later stage as the ANITA launch approaches, opportunities for attachment of small passive student experimental payloads to the main ANITA Gondola will be developed and offered.

6.2 Goals and Objectives.

Enhanced involvement of middle school girls in inquiry-based science. The ABOVE program will partner with an highly successful website, Whyville.net, to house an ANITA interactive learning center. Whyville is a virtual affinity community which offers inquiry based science activities to an underserved audience and is moderated daily. Currently, Whyville.net has 105,000 registered users, 65% of whom are middle school girls. An ANITA section in Whyville will feature information about the ANITA mission and a hot air balloon race based on principles of physics. It has received editors choice awards from Netscape, AOL.com, Hotbot, dmoz and Lycos and was a finalist for a GII Award.

Participation of underserved high school and college students in research. The DetectNet Program will involve minority and underserved participating high schools and institutions of higher education in the process of scientific research. ANITA will assist in the placement of low cost cosmic ray detection systems, which will be internet-linked throughout Oahu. These collaborations will be supported with personal contact with ANITA scientists acting as DetectNet Advisors to participating institutions. The development of small experiments to be flown with ANITA to extreme high altitudes provides an opportunity for involvement in space science at a level that few students or teachers ever achieve, and this aspect of ANITA EPO is expected to generate great interest.
Table 17: ANITA EPO. Costs are in FY 2003\$K.

<table>
<thead>
<tr>
<th>FY</th>
<th>ABOVE</th>
<th>DetecNet</th>
<th>ANITA Academics</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K</td>
<td>$K</td>
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<tr>
<td>2010</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>7</td>
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<tr>
<td>total</td>
<td>87</td>
<td>185</td>
<td>231</td>
<td>503</td>
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</table>

Capability and Commitment. As a university professor with the backing and encouragement of his department’s educational faculty, Peter Gorham, the ANITA PI, strongly supports a significant and resourceful Education and Public Outreach program as part of the ANITA Mission, with a $502K budget and active participation by all members of the ANITA science team.

6.3 Evaluation of the ANITA EPO Success.

ABOVE. Metrics of visits to the ANITA website and balloon race simulation will be gathered by the Whyville.net team and reported annually in time for entry in the EDCATS system. Based on an NSF funded project called Whygirls conducted by the Caltech Precollege Science Initiative Research Group interest in inquiry science by middle school girls can be monitored.

DetectNet. The program will seek a goal of 6 institutions, which will build, maintain and submit data to ANITA scientists for the duration of the DetectNet part of the E/PO. All information needed for EDCATS will be reported. DetectNet would also provide integration to the wider community of internet-based cosmic-ray detection facilities such as CHICOS via access to a web-based archive of cosmic ray events.

ANITA Academics. Initial support will create Pre-service teacher curricular materials in research related to the ANITA mission. Academic internships will be provided. A competition for winning student experimental payloads aboard ANITA will introduce students and teachers to the excitement of scientific competition.

6.4 Dissemination strategies.

ABOVE. Whyville.net currently is growing by 10,000 registered users a month. Interactive experiences with ANITA simulations and information by this affinity community will grow daily as visitors come to the ANITA site and disseminate the information learned.

DetectNet. The participants of the DetectNet array will write news reports of their accomplishments and experiences. These reports will be submitted to news media for publication. Presentations at conferences such as NSTA and NCTM will be promoted.

ANITA Academics. NASA media relations will be given continuing information concerning the ANITA Academics during their studies. If completion of doctoral studies is completed during the ANITA mission, special recognition of these scholars will be made by the NASA community. The post-flight reports on student experiments will be featured on ABOVE and participants will be invited to describe their results in public forums and venues.

7 NEW/ADVANCED TECHNOLOGY, & SMALL DISADVANTAGED BUSINESSES

The PI, Prof. Peter Gorham, understands NASA OSS goals for new/advanced technology transfer, and intends to address them in detail during the Phase A study. He also understands the NASA OSS requirements for participation of Small Disadvantaged Businesses and Minority Institutions, and fully intends to comply with these requirements. The University of Hawaii is a historically minority-serving institution, and will be fully involved in ANITA development. A plan to implement NASA requirements will be in place shortly after selection for Phase B development.
APPENDICES

8.1 Letters of Endorsement. We include one letter of endorsement from the Jet Propulsion Laboratory as a major contributor, taking the Project Management role.

There are no co-Investigators with planned no-exchange-of-funds contributions to ANITA. There are also no non-U.S. co-Investigators. According to section 3.5.3 of the AO, no additional letters of endorsement from the co-Investigators are therefore required until the Phase A study.
April 24, 2003

Refer to: 700-LLS:kp

Dr. Peter W. Gorham
Physics and Astronomy Department
University of Hawaii at Manoa
2505 Correa Road
Honolulu, HI 96822-2219

Dear Dr. Gorham:

Subject: Joint Proposal entitled, “Antarctic Impulsive Transient Antenna: A Long Duration Balloon High Energy Neutrino Observatory”


The Jet Propulsion Laboratory is pleased to be your partner on the subject proposal. We look forward to a productive relationship during the concept study phase and to a successful mission.

The Jet Propulsion Laboratory is committed to providing the support described in the proposal on the cost and schedule assuming that NASA funds the proposal. JPL also endorses the participation of Dr. Kurt L.wer and Dr. Charles Naudet as co-investigators on your science team.

Please refer to JPL Proposal Number 71-8122 on all written correspondence to JPL pertaining to this proposal.

If you have any questions regarding JPL’s participation on this proposal, please contact Mr. Michael Devirian of my staff at (818) 354-3993.

Sincerely,

[Signature]

Larry L. Simmons
Director
Astronomy and Physics Directorate
8.2 Statement of Work and Funding information. JPL is the NASA lead center on the ANITA SMEX Mission proposal, as submitted in response to the 2003 SMEX Announcement of Opportunity. If this mission is selected for development and launch as a SMEX mission, JPL will act as the NASA lead center for the project, providing overall project management and specific contributions to the instrument development, payload testing, integration, calibration, launch, and mission operations. The University of Hawaii will provide the lead in Science-related tasks, and in specific instrument development tasks associated with the PI’s research expertise.

Phase A concept study report. We propose that the requirement for a phase A concept study for ANITA be somewhat relaxed. We believe that the goals of the concept study will have been largely achieved through the funding already allocated to ANITA under the Space Research and Technology funding provided by the ROSS 2002 award, and will facilitate rapid completion of the phase A report.

We propose that the concept study and bridge phase be completed in a relatively compressed schedule within the first 4-5 months of FY 2004. This would be immediately followed by a confirmation review and rapid transition to Phase B, which would be facilitated by continuing efforts of the collaboration members under incremental funding from the ROSS program, which would not be phased out until the downselection of ANITA was complete. The concept study can be completed by senior members of the collaboration without serious impact on the continuing efforts that will be ongoing under the ROSS program.

General task statements for Phase B/C/D/E.

Table 18 provides a summary of general task statements for the various institutions as a function of mission phase. The major work centers during the pre-launch mission phases are expected to be JPL and UCI, with important secondary efforts divided roughly equally between the other institutions according to the local expertise and interests. We expect this matrix to become more focused during Phase A, and in particular one of the deliveries of the Phase A study will be a detailed division of labor for the secondary contributions from the universities.

Scope of Work and Government responsibilities. The scope of work for JPL, which is the contributing NASA center for ANITA, has been noted in prior sections, and we recap it here. JPL will take primary responsibility for the project management: that is, the coordination and final accountability for all phases of the mission and all deliveries and integration associated with outside contractors or participating universities. JPL will also be primarily responsible for the delivery of the RF instrument to payload integration, as well as oversight of mission assurance, calibration, and environmental testing.

Contractual arrangements for Phase A & bridge phase. Two NASA contracts are required for the Phase A and Bridge phase, one for the PI institution and one for JPL. It is anticipated that these contracts will be issued for amounts of $100 + $50K to the University of Hawaii, and $150 + $50K to JPL. We also request that, should ANITA be selected for a phase A study, that the ANITA ROSS SR&T funding continue incrementally through the Phase A study, until the final NASA selection is made, so that continuity of the project can be maintained to avoid any hiatus and associated schedule risk to the Explorer program.
Table 18: *Phase B, C/D, E general tasks.*

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<tr>
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<th>Phase C/D</th>
<th>Phase E</th>
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<td>Data acq. &amp; Analysis</td>
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<td>Digitizer development</td>
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<td></td>
<td>Trigger design</td>
<td>Trigger development</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Software design</td>
<td>Secondary SW develop.</td>
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<td>JPL</td>
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<td>RF instrument design</td>
<td>RF instr. constr/integration</td>
<td>Flight turnaround</td>
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<td>telemetry design</td>
<td>telemetry development</td>
<td>Ground telemetry</td>
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<td>Gondola Design</td>
<td>Gondola construction</td>
<td>Primary analysis, data product development</td>
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<td>Ancillary system management</td>
<td>Payload Integration</td>
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<td>Ice properties database</td>
<td>Antarctic Launch support</td>
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<td>Penn State Univ.</td>
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<td>Gondola ancillary</td>
<td>Data analysis</td>
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<tr>
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Table 19: *Phase A concept study and Bridge Phase estimated cost breakdown, in Real Year $K.*

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</tbody>
</table>
8.3 *Curriculum Vitae*

List of Investigators Providing CVs.

PROF. PETER GORHAM

PROF. STEPHEN BARWICK

PROF. JAMES BEATTY

PROF. DAVID BESSON

PROF. DOUG COWEN

PROF. MICHAEL DUVERNOIS

DR. KURT LIEWER

DR. CHARLES NAUDET

PROF. DAVID SALTZBERG

PROF. DAVID SECKEL

DR. GARY VARNER
CURRICULUM VITA
Peter W. Gorham

Profession Preparation:
♦ Ph.D., Physics, 1986, University of Hawaii at Manoa, Department of Physics & Astronomy
♦ M.S., Physics, 1983, University of Hawaii at Manoa, Department of Physics & Astronomy
♦ B.S., Physics, 1980, University of California at Irvine, Department of Physics.
♦ B.A., English Literature, 1980, University of California at Irvine, Department of English.

Appointments:
♦ Associate Professor of Physics, University of Hawaii at Manoa Department of Physics and Astronomy, August 2001 to present.
♦ Senior Member of the Technical Staff, Jet Propulsion Laboratory, California Institute of Technology, (1996-2001; joint appointment continues to present). Duties included:
  ♦ Architect, Stellar imaging subsystem, NASA Starlight Mission (Dual Spacecraft Formation flying optical interferometer)
  ♦ Project element manager, StarLight Mission Focal Plane Detector System
♦ Research Professor in Physics, University of Hawaii at Manoa Dept. of Physics and Astronomy, (1991-1996)
♦ Postdoctoral Research Associate in Physics, California Institute of Technology (1987-1989).

Awards & Recognition:
♦ 2002 U.S. Department of Energy Outstanding Junior Investigator Award for research in radio detection of high energy particles. One of only six awarded nationwide in 2002.
♦ Chair, SPIE 2002 Kona Conference on Particle Astrophysics Instrumentation.

Current and Recent Research Activities:
♦ Principal Investigator, Antarctic Impulsive Transient Antenna (ANITA), NASA Office of Space Science, Space Research & Technology Grant for Long-duration Antarctic Balloon project to detect ultra-high energy neutrinos, 2003, ongoing.
Principal Investigator, Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE). NASA/JPL/DOE-supported ongoing search for radio Cherenkov emission from ultra-high energy neutrinos and cosmic rays interacting with the lunar limb, using the 70 meter Goldstone radio telescope.

Principal Investigator, Radio Detection of High Energy Particles, a DOE-funded program under the DOE Outstanding Junior Investigator Award program, 2002., ongoing.

Principal Investigator, Characterization of the Askaryan Effect for PeV to EeV Showers, SLAC T464 experiment, completed in June 2002.

Co-Investigator, Cosmic-ray Atmospheric Zev Interaction, Los Alamos National Laboratory FORTE satellite data analysis Long-Duration Research Funding (LDRF) grant, A. Jacobson (Los Alamos) PI, 2003 ongoing.

Co-Investigator, KamLAND neutrino oscillation experiment, Kamioka Japan, 2003 ongoing.

Prior Research Activities:

1997-2001:
• Spacecraft and instrument architecture and development for various space optical interferometry projects, NASA/JPL.

1991-1996:
• Search for ultra-high energy neutrino-induced cascades from astronomical sources, observed with a deep ocean water Cherenkov detector.
• Studies of deep ocean physics related to detector development: optics, housing implosion dynamics, acoustics, galvanic effects.

1987-1991:
• Discovery of first radio pulsar in the core of a globular cluster using Arecibo 305 m telescope.
• Multiwavelength studies of supernova remnants; VLA radio imaging of remnant candidates.
• Deep pulsar survey of supernova remnants from Arecibo.
• Development of speckle interferometer detector system for Palomar 200'' telescope
• Production of first diffraction-limited optical and near-infrared images at Palomar; used to image the photosphere and molecular atmosphere of the giant Cepheid variable star Mira
• Development of imaging, photon-counting detector for Palomar 60" telescope.

1982-1986:
• Development of prototype detector data acquisition system, used to make new measurements of the cosmic-ray muon ocean depth intensity relation.
• Search for cosmic monopoles catalyzing baryon decay.
• High energy gamma-ray observations on galactic and extragalactic objects at Whipple Observatory (dissertation research).
Studies of X- and gamma-ray pulsar phenomenology, including gravitational lensing, and high energy particle beam steering effects.

Recent Invited Talks:


Selected Recent Publications:

Curriculum Vita

STEVEN W. BARWICK

Department of Physics and Astronomy
University of California
Irvine, CA 92697-4575

Phone: 949-824-2626
Email: barwick@cosmic.ps.uci.edu
WWW: http://www.ps.uci.edu/~barwick

A. Education:
Massachusetts Institute of Technology
University of California-Berkeley
University of California-Berkeley

Physics

B.S. 1981
Physics
M.A. 1983
Physics
Ph.D 1986

B. Appointments:
2000-present
Professor of Physics, University of California-Irvine
1995-2000
Associate Professor of Physics, University of California-Irvine
1990-1995
Assistant Professor of Physics, University of California-Irvine
1986-1990
Research Physicist, University of California-Berkeley

C. Selected Publications:


D. Recent honors:
JAMES J. BEATTY
Departments of Physics and of Astronomy and Astrophysics
Pennsylvania State University
University Park, PA 16802

Education:
1986  Ph.D., Physics, University of Chicago
1984  S.M., Physics, University of Chicago
1982  A.B., Physics, University of Chicago

Positions:
2001-present  Professor, Physics and Astronomy & Astrophysics, Pennsylvania State University
1995-2001  Associate Professor, Physics and Astronomy & Astrophysics, Pennsylvania State University
1994-1995  Associate Professor, Physics, Washington University in St. Louis
1991-1994  Assistant Professor, Physics, Washington University in St. Louis
1989-1991  Assistant Professor, Astronomy and Physics, Boston University
1986-1989  Research Assistant Professor, Physics, Boston University
1986  Research Associate, Physics, University of Chicago
1982-1985  Research Associate, Physics, University of Chicago

Selected Awards:

Representative Recent Publications:


DAVID Z. BESSON
Curriculum Vitae and Biographical Sketch

KU Dept. of Physics and Astronomy
Lawrence, KS 66045-2151
(785)864-4741

Birthday: Nov. 29, 1957 (Newark, NJ)
Nationality: United States
Email: dbesson@ukans.edu

Professional Preparation
1986 Ph.D. in Physics, Rutgers University, New Brunswick, NJ
  Thesis Advisor: Prof. Felix Sannes
  Thesis Title: Radiative Decays of the Υ(1S) Meson
1979 B.S. in Physics, Columbia University, NYC, NY

Appointments
1/97 - Assoc. Prof., University of Kansas, Dept. of Physics
8/93 - 12/96 Asst. Prof., University of Kansas, Dept. of Physics
9/90 - 8/93 Cornell U., Dept. of Physics, Postdoctoral Res. Assoc.
  (CLEO Collaboration “Analysis Coordinator” during that time)
1/87 - 8/90 U. of Florida, Dept. of Physics, Postdoctoral Res. Assoc.
9/88 - 12/88 Visiting Scientist, Institute of Nuclear Physics, Novosibirsk, Siberia (Russia)
6/83 - 1/87 Rutgers U., Physics Dept. Research Assistant
9/79 - 6/83 Rutgers U., Physics Dept. Teaching Assistant

Awards and Recognition
1. KU Physics Dept. Undergraduate Teaching Award (1994) for innovations in instruction.
2. Cottrell Scholar (Research Corp, Tuscon, AZ), 1995-2001
3. Mentor, four Goldwater Scholarship recipients within the last five years.
4. Named primary instructor for Kansas Regents High Academy, summer 2002. Duties included teaching 140-person class of high school juniors and seniors selected from throughout the state of Kansas to attend special summer class on cosmology at the University of Kansas (June 10, 2002 – July 5)

Selected Publications
4. Correlated Λc − Λc production in e+e- annihilations at √s ~ 10.5 GeV, A. Bornheim et al. (with the CLEO Collaboration), hep-ex 0101051, Phys. Rev. D63 (2001) 112003
DOUGLAS F. COWEN
Departments of Physics and of Astronomy and Astrophysics
Pennsylvania State University
University Park, PA 16802

Education:
1990    Ph.D., Physics, University of Wisconsin, Madison
1985    M.S., Physics, University of Wisconsin, Madison
1983    B.S., Physics, Dartmouth College, Hanover, NH

Positions:
2002-present  Associate Professor, Physics and Astronomy and
               Astrophysics, Pennsylvania State University
2001-2002  IceCube Project Science Coordinator, and Research
           Professor, Univ. of Wisconsin, Madison
1994-2002  Assistant Professor, Physics, University of Pennsylvania
1993-1994  Senior Research Fellow, California Institute of Technology
1990-1993  Research Fellow, California Institute of Technology
1985-1990  Research Assistant, University of Wisconsin, Madison

Selected Awards:
National Science Foundation CAREER award, 1999-2003, University of Pennsylvania
and Pennsylvania State University.

Representative Recent Publications:

5.  Direct Evidence for Neutrino Flavor Transformation from Neutral Current
6.  Observation of High Energy Atmospheric Neutrinos with AMANDA, E. Andres,
RESEARCH EXPERIENCE

2000- Assistant Professor
current School of Physics and Astronomy, University of Minnesota, Minneapolis, MN
Research Focus: Experimental particle astrophysics
• HEAT, HEAT-pbar, CREAM cosmic-ray balloon payloads
• Pierre Auger Observatory for the highest energy cosmic rays
• Detector and detector electronics research

1996- Research Associate (Prior to 9/99: Postdoctoral Research Fellow), Advisor: James J. Beatty
1996-2000 Department of Physics, The Pennsylvania State University, University Park, PA
1991- Graduate Research Assistant, Advisor: John A. Simpson
1996 Enrico Fermi Institute, The University of Chicago, Chicago, IL
Thesis: On the Galactic cosmic ray manganese

EDUCATION

Ph.D. Physics: University of Chicago, August 1996
M.S. Physics: University of Chicago, March 1995
B.S. Physics, with Highest Honors: Georgia Institute of Technology, June 1991

RECENT, RELEVANT ARTICLES


Curriculum Vita for Kurt M. Liewer

Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, CA 91109  

Phone: (818) 354-4751  
E-Mail: kurt.liewer@jpl.nasa.gov

EDUCATION:  
B.S. University of Washington (Physics).  1967  
Ph.D. University of Maryland (Physics).  1974  
Dissertation advisor: Douglas Currie

CURRENT POSITION:  
Principal Engineer, Jet Propulsion Laboratory.  
Formation Interferometer Testbed Architect, StarLight Project

EXPERIENCE:

•  Active in all phases of design, construction and operation of the StarLight Project Formation Interferometer Testbed. Primary expertise is in the areas of optics (interferometry), mechanics and CCD cameras.

•  A co-investigator in the search for ultra-high energy neutrinos (Goldstone Lunar Ultra-high Energy neutrino Experiment, GLUE) using Deep Space Network (DSN) radio telescopes.

•  Ten years experience as System Engineer for the DSN Tracking and Very-long-baseline Interferometry (VLBI) Systems.

•  Contributed extensively to bringing an 11-m radio antenna on line in support of the U.S. Space VLBI Project.

•  Experience with microwave hardware, digital hardware, many programming languages and operating systems, data analysis.

•  Considerable additional experience with system engineering and requirements definition.

•  Eight years of experience with VLBI hardware, software and analysis.

SELECTED PUBLICATIONS:

1. "Radio Limits on an isotropic flux of >100 EeV neutrinos,"
Curriculum Vitae  Charles J. Naudet, Jr.

Correspondence Address:  
MS 238-700, Jet Propulsion Laboratory  
4800 Oak Grove Drive, Pasadena CA.  
(818) 354-2053 (office)  
Email: charles.j.naudet@jpl.nasa.gov

Professional:  
Manager of the Deep Space Tracking Systems Group, 2003- present  
Member of the Senior Staff, Jet Propulsion Laboratory, 1999-2003  
Member of the Technical Staff, Jet Propulsion Laboratory, 1994-1999  
Staff Scientist, Lawrence Berkeley Laboratory, 1986-1994

Education:  
B.S. Engineering Physics, 1979, University of Kansas  
M.A. Physics, 1983, Rice University, Thesis: *A Monte Carlo Study of High Transverse Energy Triggers in pp Collisions at P_{lab}=400 GeV/c.*  
Ph.D Physics, 1986, Rice University, Thesis: *A Study of Large Transverse Events in pp and πp Interactions at P_{lab}=200 GeV/c and Evidence for Higher-Twist Effects.*

Experience:  
Co-I on the KQ VLBI Survey Collaboration. This international collaboration has been formed with the objective of extending the International Celestial Reference Frame (ICRF) to K-band and Q-band frequencies, extending the VLBA calibration source, and providing a candidate list for Ka-band observations with flux and structure variability that is suitable for navigational applications.  
Co-I on Kollaboration. This collaboration is formed between members of Japan’s Communication Research Laboratory and the Deep Space Tracking Systems group at JPL. The Kollaboration will have the objective of performing a detailed radio source survey at Ka-band and to produce the first celestial reference frame at Ka-band frequencies.  
CO-I on ANITA (ANtarctic Impulsive Transient Antenna) which was funded under NASA’s ROSS program. ANITA is a balloon borne radio Cherenkov instrument optimized for detection of radio frequency pulses created by ultra-high energy neutrinos interacting with the Antarctic’s ice fields.  
Co-I on the GLUE experiment (Goldstone Lunar Ultra-high Energy neutrino Experiment), which received a “Caltech Presidents Research Grant” in fiscal 2000 and is currently close to acquiring over 120 hours of data at the DSN’s Goldstone complex.  
The Deep Space Network’s (DSN) Very Long Baseline Interferonomy (VLBI) lead system engineer, and the task manager and Science Service Engineer for the DSN’s VLBI element.

Selected Publications:  
DAVID P. SALTZBERG
UCLA Department of Physics and Astronomy

Research Fields: Experimental High Energy Physics; Neutrino Astronomy

Education:
(Dissertation: “Measurement of the Mass of the W Boson”)
A.B., Princeton University, Princeton, New Jersey, 1989, Physics

Awards and Recognition:
Dept. of Energy Outstanding Junior Investigator, 2000
NSF Career Award, 2000
Alfred P. Sloan Fellow, 1999
Gainier Foundation Fellow, 1994 (Univ. of Chicago, Physics Dept.)
Nathan Sugarman Award, for Ph.D. work, 1993 (Univ. of Chicago, Physics Dept.)
McCormick Scholarship (Univ. of Chicago), 1989–1993
National Science Foundation Fellow, 1990–1993
Kusaka Award, for independent work, 1988 (from Princeton Univ., Physics Dept.)

Professional Positions:
Associate Professor, Department of Physics and Astronomy, University of California, Los Angeles (UCLA), Los Angeles, California, 2002 to present.
Assistant Professor, Department of Physics and Astronomy, University of California, Los Angeles (UCLA), Los Angeles, California, 1997 to 2002.
Paid Scientific Associate, CERN – Particle Physics Experiments Division (Chorus Experiment), Geneva, Switzerland, 1995 to 1997.

Selected Publications:
(a) **David Seckel**: B.A., Physics, Brown University, 1976; M.S., Physics, University of Washington, 1981; Ph.D., University of Washington, 1983.

(b) **Appointments**: Associate Professor, University of Delaware, 2000-present; Associate Professor, Bartol Research Institute 1993-2000; Assistant Professor, Bartol Research Institute, 1998-1993; Post Doctoral Research Associate, University of California at Santa Cruz, 1985 and 1987-1988; Paid Associate, Theory Division, CERN, 1986; Post Doctoral Research Associate, Theoretical Astrophysics Group, Fermilab, 1983-1985.

(c1) **Five publications relevant to research proposal:**

(c2) **Five additional publications:**

(d) **Synergistic Activities**: Local Outreach: presentations at “High School Physics Day”, “Space Day”, local elementary schools, Center for Lifelong Learning; Judge for Science Olympics.

(e) **Collaborators and Other Affiliations:**
(ii) **Graduate and Post-Doctoral Advisors**: A. Zee (thesis), E. Kolb, J. Ellis, J. Primack (postdoctoral)
(iii) **Thesis Advisor and Postgraduate Scholar Sponsor**: Five years: George Frichter (postdoctoral scholar); Student Total 1; Postdoctoral Total 1.
Gary S. Varner

1. **Professional Preparation:**

   - Boston University: Electrical Engineering B.S.E.E. 1989
   - Boston University: Physics M.A. 1995
   - University of Hawaii: Physics Ph.D. 1999

**Appointments:**

- 2002-present: Director, Univ. of Hawaii Instrumentation Development Laboratory
- 2000-2002: Principal Engineer/Sr. Scientist, AOptix Technologies
- 1998-2000: Electrical Engineer/Researcher, University of Hawaii
- 1997-1998: Visiting Project Engineer, CERN & LIP, Portugal
- 1995-1997: Research Associate, University of Hawaii
- 1994-1995: Adjunct Professor, Wentworth Institute of Technology
- 1993-1995: Senior Electrical Engineer/Physicist, Boston University
- 1992-1993: Physics Design Engineer, Boston Univ & SSC Laboratory

**Awards & Recognition:**

- Research Fellowship, Laboratory of Instrumentation and Particles, Portugal 1997.
- R&D 100 Award for development of Time Stretcher circuit, 1997.
- Coordinator, Cathode Strip Chamber anode subsystem, SSCL GEM detector, 1993.

**Selected Publications:**


**Selected Patents:**

- "A Monolithic Charge Integrating Wavefront Sensor Readout", patent rights held AOptix Tech
- "An Integrated Charge Pump HV Bi-morph Mirror Driver", patent rights held AOptix Tech
8.4 Draft International Participation Plan/Compliance with Export Rules.
There is no international participation in the ANITA Mission at this time and none is envisioned in the future. However, the proposal team is cognizant of the issues delineated in the AO regarding compliance with U.S. export laws and regulations. Specifically, the U.S. International Traffic in Arms Regulations (ITAR) and Export in Arms Regulations (EAR) will be carefully followed in all instances where they apply to the ANITA Mission.

8.5 Assignment of Technical Responsibilities between US and International Partners. ANITA has no international participation at present. No assignment of responsibilities is necessary. (See previous item).

8.6 Orbital Debris Generation Acknowledgment Statement. ANITA will not launch any material into orbit. No further statement is necessary.

8.7 NASA PI proposal team information. Because the Principal Investigator maintains a joint status with both JPL and the University of Hawaii, we provide here a description of the process by which the non-Governmental members of the proposing team were included.

The ANITA concept developed very quickly based on discussions that arose originally out of the RADHEP 2000 conference held at UCLA in November 2000. At that meeting the concept of a balloon experiment over Antarctic ice was first informally presented. The concept was not further developed or discussed after that time, but later, after encouragement by JPL management, the concept was revisited in early summer of 2001. After the results from adaptation of the modeling codes discussed above indicated significant promise for the idea, the PI asked for independent confirmation from a collaborator (Prof. Saltzberg) who was one of the few other investigators known to be working in this field. Once preliminary confirmation was given, the PI and Prof. Saltzberg then both contacted the spokesmen of the two major U.S. neutrino observatories in operation or planning stages, Prof. Barwick of the AMANDA, and Prof. Halzen of IceCube.

When both of these investigators endorsed the project, the PI then requested their recommendations for a potential science team, based on several factors:

- The need for significant and diverse balloon expertise on the project.
- Credible experience and recognition in either high energy cosmic ray astrophysics or high energy neutrino astrophysics.
- Availability and willingness to participate and make a significant contribution.

Prof. Barwick then proceeded to informally publicize the opportunity for science team participation among attendees of the International Cosmic Ray Conference in Hamburg, Germany in mid-August. This meeting, which occurs every other year, is the premier conference in the field of high energy cosmic rays and neutrinos, and thus provided an ideal venue to inform and assess the interest of potential participants.

The present size of the (non-JPL) participating team, with twelve members in addition to the PI, achieves an appropriate balance in which all of the members will have opportunities to make important contributions without any excessive burden.

The Principal Investigator has no personal financial interest in any aspect of the proposed investigation for ANITA, including all hardware and software development, ground data systems, or any other proposed work. The PI is therefore aware of no conflict of interest, potential or real, in his involvement with the ANITA project.
### 8.8 Abbreviations & Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABOVE</td>
<td>Antarctic Balloon Observatory Virtual Explorer</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-to-digital converter</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nuclei</td>
</tr>
<tr>
<td>AMANDA</td>
<td>Antarctic Muon and Neutrino Detector Array</td>
</tr>
<tr>
<td>ANITA</td>
<td>Antarctic Impulsive Transient Antenna</td>
</tr>
<tr>
<td>AO</td>
<td>Announcement of Opportunity</td>
</tr>
<tr>
<td>ATA</td>
<td>Allen Telescope Array</td>
</tr>
<tr>
<td>AWA</td>
<td>Argonne Wakefield Accelerator</td>
</tr>
<tr>
<td>CBE</td>
<td>Current Best Estimate</td>
</tr>
<tr>
<td>CHICOS</td>
<td>California High School Cosmic-ray Observatory</td>
</tr>
<tr>
<td>CMBR</td>
<td>Cosmic Microwave Background radiation</td>
</tr>
<tr>
<td>CSU</td>
<td>California State University</td>
</tr>
<tr>
<td>CV</td>
<td>Curriculum vita</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-analog converter</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>EAR</td>
<td>Export in Arms Regulations</td>
</tr>
<tr>
<td>EDCATS</td>
<td>Education Program Data Collection and Evaluation System</td>
</tr>
<tr>
<td>EeV</td>
<td>Exa-electron volt (10^{18} eV)</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic interference</td>
</tr>
<tr>
<td>EMP</td>
<td>Electromagnetic pulse</td>
</tr>
<tr>
<td>EP/0</td>
<td>Education and Public Outreach</td>
</tr>
<tr>
<td>EUSO</td>
<td>Extreme Universe Space Observatory</td>
</tr>
<tr>
<td>FORTE</td>
<td>Fast On-orbit Recording of Transient Events</td>
</tr>
<tr>
<td>FY</td>
<td>Fiscal Year</td>
</tr>
<tr>
<td>GLUE</td>
<td>Goldstone Lunar ultra-high energy neutrino Experiment</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GZK</td>
<td>Greisen-Zatsepin-Kuzmin</td>
</tr>
<tr>
<td>HDPE</td>
<td>High density polyethylene</td>
</tr>
<tr>
<td>HK</td>
<td>Housekeeping</td>
</tr>
<tr>
<td>HMSC</td>
<td>Historically Minority Serving Campus</td>
</tr>
<tr>
<td>HOPA</td>
<td>Hawaii Observatory for Particle Astrophysics</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate frequency</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>ITAR</td>
<td>International Traffic in Arms Regulations</td>
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<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>LISA</td>
<td>Laser Interferometer Space Array</td>
</tr>
<tr>
<td>LNA</td>
<td>Low-noise amplifier</td>
</tr>
<tr>
<td>LDB</td>
<td>Long-duration balloon</td>
</tr>
<tr>
<td>LoE</td>
<td>Letter of Endorsement</td>
</tr>
<tr>
<td>LPZZ</td>
<td>Log-periodic zig-zag antenna</td>
</tr>
<tr>
<td>MDF</td>
<td>Minimum detectable flux</td>
</tr>
<tr>
<td>MBH</td>
<td>Massive Black Hole</td>
</tr>
<tr>
<td>NESTOR</td>
<td>Neutrino Extended Submarine Telescope with Oceanographic Research</td>
</tr>
<tr>
<td>OSS</td>
<td>Office of Space Science</td>
</tr>
<tr>
<td>PeV</td>
<td>Peta-electron volt (10^{15} eV)</td>
</tr>
<tr>
<td>PI</td>
<td>Principal investigator</td>
</tr>
<tr>
<td>PM</td>
<td>Project Manager</td>
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<tr>
<td>PV</td>
<td>Photo-Voltaic</td>
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<tr>
<td>RAND</td>
<td>Radio Antarctic Neutrino Detector</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio frequency Interference</td>
</tr>
<tr>
<td>RICE</td>
<td>Radio Ice Cherenkov Experiment</td>
</tr>
<tr>
<td>SCA</td>
<td>Switched Capacitor array</td>
</tr>
<tr>
<td>SEU</td>
<td>Structure and Evolution of the Universe</td>
</tr>
<tr>
<td>SIP</td>
<td>Support Instrument package</td>
</tr>
<tr>
<td>SK</td>
<td>Super-Kamiokande</td>
</tr>
<tr>
<td>SNO</td>
<td>Sudbury Neutrino Observatory</td>
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<tr>
<td>SMEX</td>
<td>Small Explorer</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>SR&amp;T</td>
<td>Space Research and Technology</td>
</tr>
<tr>
<td>SW</td>
<td>Software</td>
</tr>
<tr>
<td>TD</td>
<td>Topological Defect</td>
</tr>
<tr>
<td>TDRSS</td>
<td>Telemetry data recovery</td>
</tr>
<tr>
<td>TEKR</td>
<td>Teacher Education K-12 Relations</td>
</tr>
<tr>
<td>TeV</td>
<td>Tera-electron volt (10^{12} eV)</td>
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<tr>
<td>TIGER</td>
<td>Trans-Iron Galactic Element Recorder</td>
</tr>
<tr>
<td>TLM</td>
<td>Telemetry</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra-High Frequency</td>
</tr>
<tr>
<td>ULDB</td>
<td>Ultra-long duration balloon</td>
</tr>
<tr>
<td>UT</td>
<td>Universal time</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>WB</td>
<td>Waxman-Bahcall</td>
</tr>
<tr>
<td>WBS</td>
<td>Work Breakdown Structure</td>
</tr>
<tr>
<td>XRB</td>
<td>X-ray Binary</td>
</tr>
</tbody>
</table>
REFERENCES

8.9 References

References


[47] see D. Seckel, op. cit.


